NASA/CR—2008-214841

Unmanned Aircraft System Control and ATC Communications Bandwidth Requirements

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Executive Summary

E.S.1 Introduction

There are significant activities taking place to establish the procedures and requirements for safe and routine operation of unmanned aircraft systems (UAS) in the National Airspace System (NAS). Among the barriers to overcome in achieving this goal is the lack of sufficient frequency spectrum necessary for the UAS control and air traffic control (ATC) communications links. This shortcoming is compounded by the fact that the UAS control communications links will likely be required to operate in protected frequency spectrum, just as ATC communications links are, because they relate to "safety and regularity of flight." To support future International Telecommunications Union (ITU) World Radio Conference (WRC) agenda items concerning new frequency allocations for UAS communications links, and to augment the Future Communications Study (FCS) Technology Evaluation Group efforts, NASA Glenn Research Center has sponsored a task to estimate the UAS control and ATC communications bandwidth requirements for safe, reliable, and routine operation of UAS in the NAS. This report describes the process and results of that task. The study focused on long-term bandwidth requirements for UAS approximately through 2030.

E.S.2 Task Process and Analysis

The task workflow diagram shown in Figure 1 provides an overview of the methodology used to perform this task. As shown in the figure, it roughly followed a parallel track of UAS control communications and ATC communications bandwidth analysis activities, with common processes during the initial and final stages of the task.

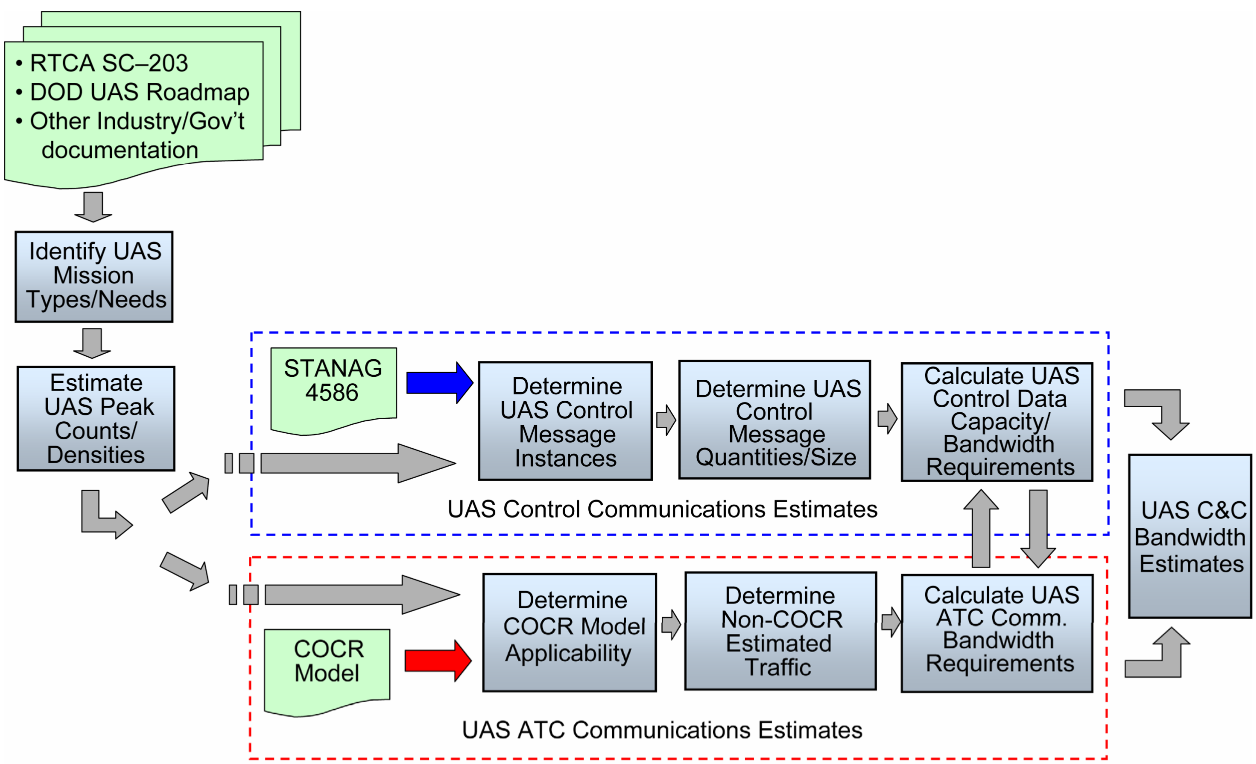


Figure 1.—Task workflow diagram.

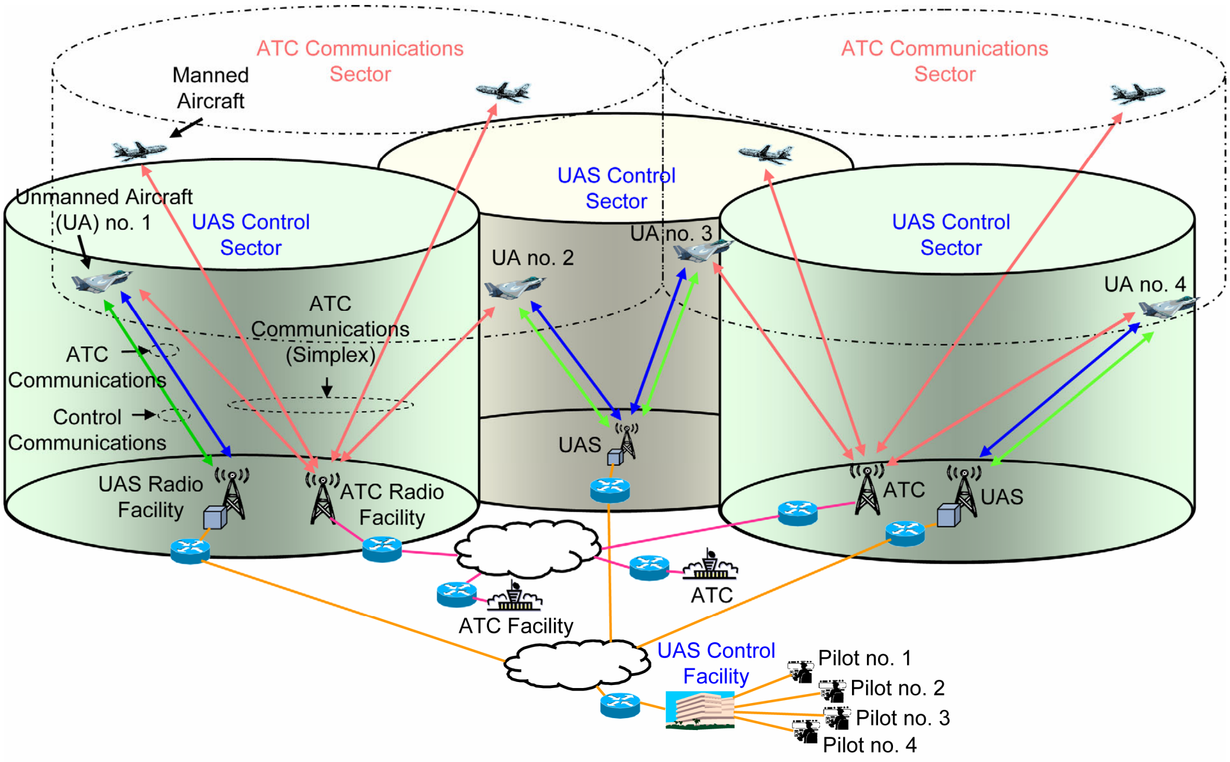


Figure 2.—UAS line-of-sight communications architecture assumed for the task.

This task was based on the concept that both control and ATC communications will be provided via a sectorized air/ground line-of-sight (LOS) communications architecture. This architecture is illustrated in Figure 2.

The assumed architecture included up to seven separate links that may be required to provide control communications and both voice and data ATC communications, as follows:

- Existing ATC radio facility to unmanned aircraft (UA) link: Channel for ATC communications shared with all aircraft in sector as shown in red (currently simplex very high frequency (VHF) double sideband amplitude modulation (DSB–AM)) (Not part of estimation)
- New UAS radio facility to UA links
  - Dedicated voice and data channels for ATC communications (uplink and downlink) as shown in blue—up to four links
  - Dedicated channels for control communications (uplink and downlink) as shown in green—up to two links

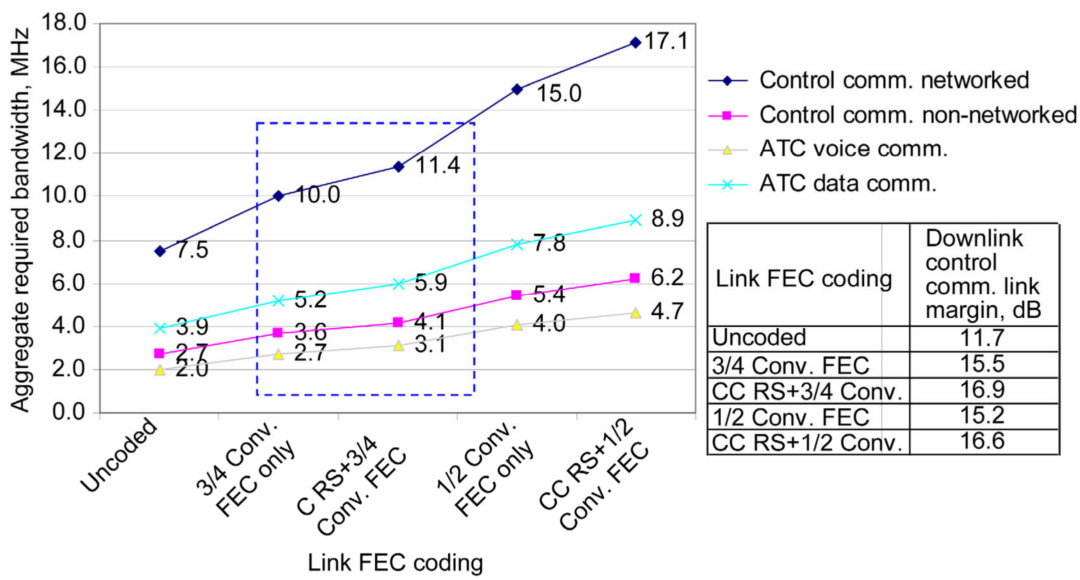
E.S.3 Task Results, Conclusions, and Recommendations

It was found that the total required UAS communications bandwidth requirements were quite sensitive to certain parameters and study assumptions, including the following:

- UA peak counts
  - UA were assumed to be 10 percent of the total peak instantaneous aircraft count (PIAC); a different value based on emerging plans and future operational practice linearly scales the results.
- UAS control communications link architecture configuration assumptions

  - Required UAS control communications data capacity was estimated for two configurations defined by Standardization Agreement (STANAG) 4586 (ref. 1), corresponding to two alternative UAS ground control station to UA link architectures. One configuration (Configuration A) assumed a non-networked, native, or proprietary-type radiofrequency (RF) link with some security overhead, while the second configuration (Configuration B) implied an RF link that included overhead for standards-based security, STANAG 4586 data link interface (DLI) wrappers, and transport/network layer protocols.
    - Configuration B resulted in significant network and transport layer protocol overhead on the air/ground (A/G) links.
    - The Configuration A non-networked assumption significantly reduced required bandwidth.
- Data rate requirements of the UAS Command and Status/Telemetry messages
  - These are highly dependent on update rates associated with varying degrees of autonomy. Conservative values were assumed to upper bound the aggregate rate, based on low to moderate autonomy UAS.
  - In addition, for the networked Configuration B, a conservative assumption was made that multiple command/status messages were not combined into internet protocol (IP) datagram payloads; that is, each IP data payload consisted of only one command/status message.
- The channel modulation selected and amount of link forward error correction (FEC) coding necessary to increase link margin to accommodate excess path losses, directly impacted required channel bandwidth
  - A range of link FEC coding alternatives were used to provide a range of total required bandwidth.
  - Sector architecture, including sector size and "layering," and the corresponding selection of reuse parameters to mitigate co-channel interference.

Figure 3 illustrates required total UAS control and ATC communications bandwidth estimates for the notional architecture developed for this study for each link type considered and their sensitivity to overhead and link FEC coding assumptions. A box has been placed around the values that provide a reasonable range of bandwidth requirements, while still providing suitable performance.



Link FEC coding	Downlink control comm. link margin, dB
Uncoded	11.7
3/4 Conv. FEC	15.5
CC RS+3/4 Conv.	16.9
1/2 Conv. FEC	15.2
CC RS+1/2 Conv.	16.6

Figure 3.—Required total UAS communications bandwidth estimates and their sensitivity to overhead and link FEC coding assumptions.

Given the fact that UAS civil and private aviation in the NAS[1] is still in its earliest stages, the range of possibilities for implementing a broadbased means of providing both UAS control communications and ATC communications is fairly wide open. Because of its focus on the need to identify potential future UAS frequency spectrum needs in support of WRC activities, this study concentrated on just one of several possible means of providing these capabilities, that is, by way of UA relay as illustrated in Figure 2. Other potential architectures are being considered by RTCA SC–203, if not by other organizations. Even within this one architectural approach there are still many practical variables and uncertainties in developing the assumptions and the notional architecture design decisions needed to make the UAS communications bandwidth estimates. The sensitivity of this estimation process to these design decision assumptions and selection of certain key parameters was discussed, and this demonstrated the inadvisability of trying to derive a single number to estimate total bandwidth requirements. Therefore for this study a range of estimated bandwidth requirements was developed to provide bounds, based on the stated configurations and assumptions.

For the selected notional architecture, the findings based on modest FEC coding, such as provided by the two rate ¾-cases provide the most reasonable compromise between performance and bandwidth within the range of results. In particular, the concatenated Reed Solomon (255, 223) block encoding and ¾ rate convolutional FEC coding case provided significant excess path margin for protection against interference sources and signal degradations, including protection against burst errors. These two cases resulted in the following bandwidth estimates:

- Control communications bandwidth estimates on the order of 10 to 11.4 MHz for the networked configuration
  - 8.5 to 9.7 MHz for the UA to UAS radio control station downlink
  - 1.5 to 1.7 MHz for the UAS radio control station to UA uplink
- Control communications bandwidth estimates on the order of 3.6 to 4.1 MHz for the non-networked configuration
  - 3.3 to 3.8 MHz for the UA to UAS radio control station downlink
  - About 0.3 MHz for the UAS radio control station to UA uplink
- ATC voice communications bandwidth estimates on the order of 2.7 to 3.1 MHz, split equally between the uplink and downlink
- ATC data communications bandwidth estimates on the order of 5.2 to 5.9 MHz
  - About 3.3 to 3.8 MHz for the downlink
  - About 1.9 to 2.1 MHz for the uplink

The notional architecture used to estimate total bandwidth requirements allowed for significant link margin because of the modest sector radii. Other possible architectures may be more efficient.

Some additional summarizing remarks and recommendations can be made. Because a detailed design was beyond the scope of this task, several relevant issues were not considered. These include the following:

- Co-site interference issues, both on the UA and for the UAS ground radio facilities, not considered for this study, need to be explored. Assume that both the control communications and ATC communications use the aeronautical L-band allowed for straightforward analysis; however, simultaneous transmission on these links present serious design challenges, especially on the UA, to mitigate potential co-site interference.

[1]Military UAS were not considered in this task.

- The potential impacts of sub-banding need to be addressed. Though in certain respects it might be easier to identify noncontiguous “chunks” or sub-bands of spectrum for the different control and ATC communications links than it would be to find 10 to 20 contiguous MHz of available bandwidth to manage, this spectrum management issue should be investigated.
- The entire issue of whether or not a national UAS communications service could be implemented was beyond the scope of this study, and to a certain extent, it does not affect the analysis. However, this study was based on a uniform design, regardless of how and by whom it would be implemented and/or operated, and the study results are therefore dependent on this assumption.
- Just as with the Communications Operating Concept and Requirements (COCR), for estimation purposes, this study nominally assumed a uniform density of aircraft throughout a sector and/or service volume. In reality, this often is not the case, as both manned and unmanned aircraft would be concentrated along particular corridors or “hot spots.” This could affect UAS bandwidth requirements and should be considered as a future topic of study.
- For the purposes of link efficiency and interference mitigation, it might be advisable to combine the ATC voice and data links. Furthermore, each of the uplink/downlink pairs might be implemented via simplex or full duplex links, potentially reducing the number of UAS radio facility to UA links to as few as two. In the limit, control communications and ATC communications message traffic could be combined and implemented via a single link, though this potential single point of failure configuration might present too much risk. This issue needs further investigation.
- Though the target 10-dB link margin was mostly exceeded over the range of link parameter values assumed for the link analyses, further work in the area of required link margin, including acceptable excess path loss, should be pursued.

Contents

1.0 Background and Introduction

1.1 Background

There are significant activities taking place to establish the procedures and requirements for safe and routine operation of unmanned aircraft systems (UAS) in the National Airspace System (NAS). Among the barriers to overcome in achieving this goal is the lack of sufficient frequency spectrum necessary for the UAS control and air traffic control (ATC) communications links. This shortcoming is compounded by the fact that the UAS control communications links will likely be required to operate in protected frequency spectrum, just as ATC communications links are, because they relate to “safety and regularity of flight.” Related to this spectrum issue and concurrent with the UAS standards development activities are the ongoing efforts within the international aviation community to develop requirements for next generation aeronautical communications systems. Several recent and current activities relevant to both UAS and aeronautical communications have included the following:

- (2004 to 2006) The NASA Glenn Research Center team supporting NASA’s Access 5 Project defined functional communication requirements for UAS.
- (2004 to present) The FAA/NASA/EUROCONTROL Future Communications Study (FCS) is identifying requirements and technologies for the future radio system.
  - The Communications Operating Concept and Requirements (COCR) (ref. 2) for the Future Radio System, which drives the technology evaluations, acknowledges the potential future impact of UAS, and implicitly includes UAS in its capacity analyses.
- (2004 to present) The RTCA SC–203 UAS Control and Communications Working Group is addressing UAS communications spectrum requirements.
- (2006 to present) International Telecommunications Unit (ITU) World Radio Conference (WRC) planning activities include the U.S seeking an agenda item for WRC–11 addressing UAS communications spectrum requirements.

To support future ITU WRC agenda items concerning new frequency allocations for UAS communications links, and to augment the FCS Technology Evaluation Group efforts, Glenn has sponsored a task to estimate the UAS control and ATC communications bandwidth requirements for routine operation of UAS in the NAS. This report describes the process and results of that task.

1.2 Task Objectives and Scope

Figure 4 depicts the RTCA 203 UAS notional architecture, which includes the two principal types of UAS communications links (ref. 3):

- Control link: The equipment and links used for receiving commands from pilots in the control segment (telecommand uplink) and for transmitting aircraft health, status, and situation awareness data to the control segment (telemetry downlink). Because the UAS may be operated in both LOS (line of sight) and BLOS (beyond line of sight) conditions, this functionality may be provided by more than one data link subsystem.
- ATC communications links: Consist of equipment and links used for voice and data communications between the pilot in the control segment and an air traffic controller as well as other participants and users of the airspace.

The objective of this task was to estimate future bandwidth requirements for these two UAS communications types needed for safe, reliable, and routine operation in the NAS, in support of U.S. WRC preparation activities. The study focused on long-term bandwidth requirements for UAS approximately through 2030.

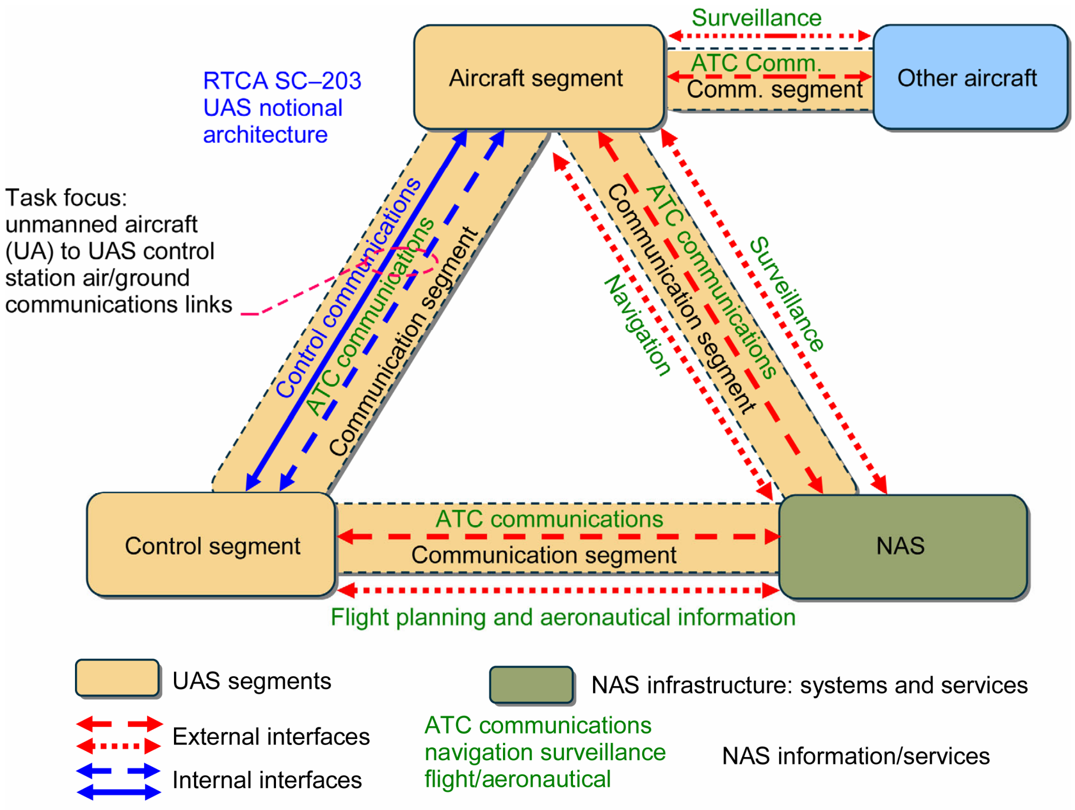


Figure 4.—UAS notional architecture showing task focus.

As seen in the figure, control communications is provided strictly between the UAS Control Segment and the Aircraft Segment (i.e., the unmanned aircraft or UA) by way of radiofrequency (RF) air/ground (A/G) link. The figure also reveals that UAS to ATC communications connectivity can be provided through several alternatives in one or more combinations of A/G and terrestrial links. The multiplicity of alternative approaches is the subject of study efforts within the RTCA SC–203 UAS Control and ATC Communications (C&C) Working Group.

Because of specific interest in supporting future ITU WRC RF spectrum activities, this task focused on a specific LOS A/G link architecture that features direct UAS control communications connectivity and ATC communications that relies on the UA to provide a relay function between the NAS ATC facilities and the UAS Control Segment. This link architecture is described in more detail in section 1.4.2.

1.3 Approach

The task workflow diagram shown in Figure 5 provides an overview of the methodology used to perform this task. As shown in the figure, it roughly followed a parallel track of UAS control communications and ATC communications bandwidth analysis activities, with common processes during the initial and final stages of the task. Each of the subtasks shown in the figure is described in the following sections.

An important part of the task methodology was the presentation of three status briefings to key Federal Aviation Administration (FAA) and NASA representatives and some of their technical support contractors over the 7-month duration of the task. These provided the opportunity to solicit and receive insightful feedback and direction to help maintain the appropriate focus of the task.

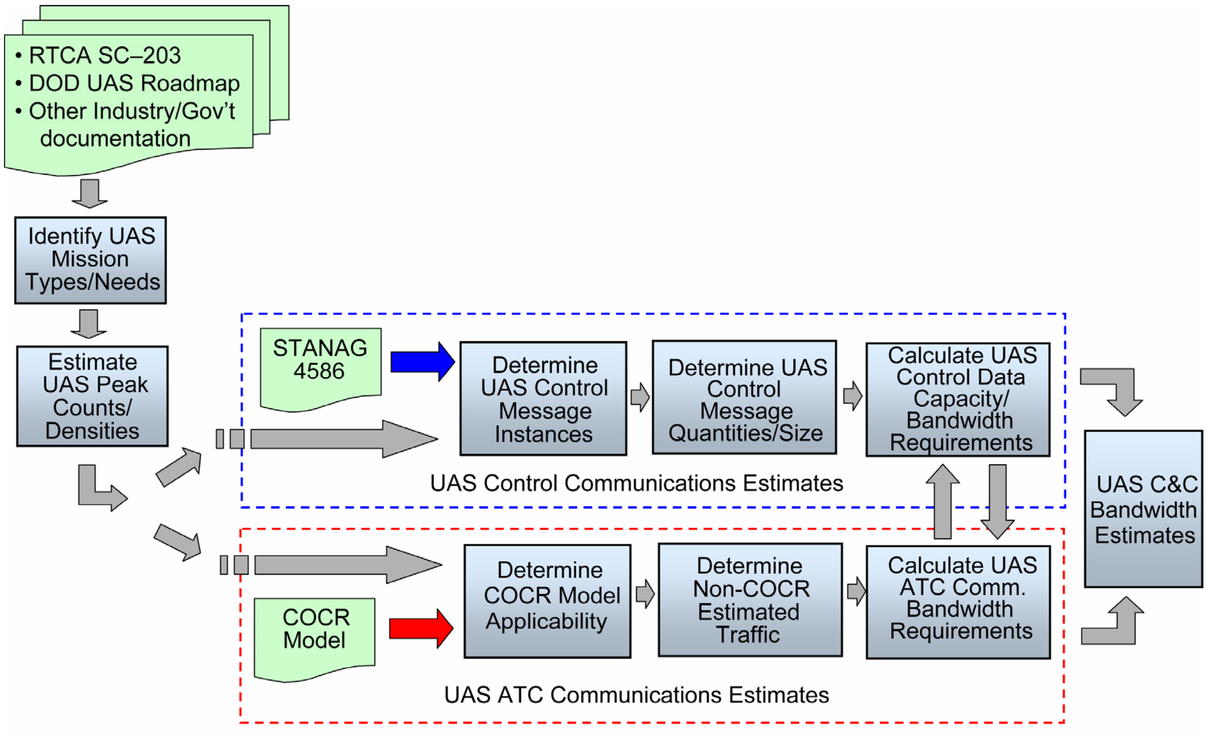


Figure 5.—Task workflow diagram.

1.3.1 Identifying UAS Mission Types and Needs

The Future Communications Study COCR models for air traffic services are based primarily on a gate-to-gate operational scenario typified by traditional manned aircraft flights and necessarily feature homogenous service volumes, flight durations, peak instantaneous aircraft counts (PIACs), and other homogeneous operational statistics. However, some augmentation needs to be made to accommodate "new" UAS operating concepts. Thus, it is important to be able to define the UAS communications characteristics that are both common to and distinct from typical communications characteristics of manned aircraft. This was accomplished in this subtask by reviewing and evaluating over 60 UAS missions and operational scenarios descriptions developed in RTCA SC–203. In addition to providing useful operational information such as expected flight durations, altitudes of operation, and mission descriptions for specific UAS, these descriptions provided some high-level communications characteristics. Table I and Table II are examples of the UAS mission/scenario information provided by the RTCA SC–203 guidance material.

Table I.—Example of UAS scenario description and flight characteristics (ref. 3)

Scenario 7, Communication Repeater
7b. Scenario Description: Multiple UAVs used together to create a continuous repeater/relay for UHF communications over remote areas. First vehicle is launched from airport and proceeds to the loiter fix. Second vehicle is launched halfway through first vehicle mission time to nonconflicting loiter fix. Once second vehicle is established at its respective fix, first vehicle returns to original launch airport via preprogrammed route. Vehicle is met upon return and towed to ramp.
8. Define characteristics of scenario for each phase of flight
a. Pre-flight: Normal airworthiness pre-flight and check of communication equipment for operation.
b. Taxi operations: Manually controlled taxi with voice communications to obtain clearance and discrete beacon code
c. Takeoff/departure: Manually controlled to departure gate
d. En-route (outbound): Preprogrammed and autonomous operation to loiter fix
e. Mission area: Racetrack loiter area, 10 miles in length
f. En-route (inbound): Autonomous fix departure to arrival gate
g. Approach/landing: Manually controlled and approach utilizing current approach procedures
f. Post-flight: Exits runway and shuts down; manually towed to recovery area

Table II.—Example of UAS scenario description performance characteristics (ref. 3)

9. Define system performance characteristics—Aircraft
a. Max. speed: 400 TAS
b. Cruise speed: 350 TAS
c. Min. speed: 90 KTS
d. Climb rate: 3500 fpm
e. Descent rate: 3500 fpm
f. Max. altitude: >60 000 MSL
g. Typical op alt: 51 000 MSL
h. Turn rate: 3 deg/s
i. Gross TO rate: 25 600 lb
j. Payload capacity: 20 000 lb
k. Endurance: 35 hr
l. Range: >12,000 nm
10. Define system performance characteristics—Airspace utilized
a. ×
b. ×
c. ⊗
d. ⊗
e. ⊗
f. ⊗
11. Define system performance characteristics—Communications links
a. Primary command/control link: INMARSAT or equivalent
b. Secondary command/control link: UHF/HF
c. Primary sensor data link:
d. Secondary sensor data link:
e. ATC voice communications: HF
f. Other communications links:
g. Security/information assurance methodology:
12. Define system performance characteristics—Operations
a. Taxi method: Human escort
b. Launch method: Rolling
c. Launch environment: Towered airport
d. Recovery method: Rolling
e. Man/machine control level: Autonomous route plan-man monitors
f. Mission type: Loitering
g. VFR/IFR: IFR
h. Operation type: Scheduled
i. Pilot/operator qualification: FAA certified manned aircraft pilot
j. Navigation: GPS/INS
13. Describe weather-related operational constraints
None
14. Describe contingency handling methodology
Preprogrammed to return to home base if communications fail. For engine failure, preprogrammed to proceed to closest identified landing site. Manual control for attempted landing.

1.3.2 Estimating UAS Peak Counts and Densities

A critical parameter in estimating UAS communications bandwidth is the number of unmanned aircraft actually flying in the NAS for the time period of interest, that is, approximately through 2030. This subtask involved identification and review of future UAS projections to make a reasonable estimate of how many UA, as a percentage of the total number of flights in the NAS, might be flying in the NAS in the future.[2]

[2]Just as with the COCR, for estimation purposes, this study nominally assumed a uniform density of aircraft throughout a sector and/or service volume. In reality, this often is not the case, as both manned and unmanned aircraft would be concentrated along particular corridors or “hot spots.” This could affect UAS bandwidth requirements and should be considered as a future topic of study.

1.3.3 Calculating UAS Control Communications Data Capacity

This activity string included a series of subtasks to determine UAS control communications data requirements, including determining UAS control message statistics, such as instances (how often they occur), size, and quantities; defining a control communications sector architecture; and performing link analyses to determine suitable channel bandwidth. The sector architecture and channel bandwidth were then used to determine the total number of control communications channels, and hence the total required UAS control communications bandwidth.

1.3.4 Calculating UAS ATC Communications Data Capacity

The FCS COCR developed per aircraft A/G data capacity requirements for providing future air traffic services (ATS). This activity string included an effort to determine the applicability of these COCR requirements to the UAS case. COCR assumptions, analysis, and results were evaluated to make this determination and to identify any potential non-COCR-defined ATC communications traffic necessary for operating UAS in the NAS. The UAS ATC data capacity requirements resulting from this analysis were then used as inputs to link budget calculations that allowed the selection of suitable modulation and forward error correction (FEC) coding techniques, and hence appropriate channel bandwidth. Also determined was a suitable technical approach to providing ATC digitized/vocoded voice communications traffic and the associated data requirements and channel bandwidth needed to provide this traffic.

1.3.5 Estimating UAS Control and ATC Communications Bandwidth

The preceding steps estimated projected future UA PIACs and densities, and the UAS control and ATC communications data rates necessary to transfer messages between a UAS control station and a low to medium autonomy UA. This step converted the UA densities and data requirements into the required bandwidth necessary to provide for all the UA flying in the NAS. The process included selecting appropriate channel access approaches for the UAS control and ATC communications links; defining an appropriate sector architecture to determine A/G link slant ranges and the number of channels needed; identifying suitable modulation and FEC coding and other link parameters to determine the required channel bandwidth for each of the links; and then multiplying the number of required channels by the channel bandwidths of each of the required links to provide an aggregate required bandwidth.

As it was determined that the UAS control and ATC communications bandwidth estimation process was highly sensitive to the selection of the above-mentioned input parameters and configurations, some high-level sensitivity analysis was performed to quantify the extent of this sensitivity and to provide some bounds on the range of values for these estimates.

1.4 Assumptions

As is usually the case, several modeling and architecture assumptions were made in the performance of this task. Some initial task assumptions were later changed or removed after it was determined that they resulted in unsatisfactory or incomplete results. The following sections list the assumptions that applied to this task.

1.4.1 Task Modeling Assumptions

The following assumptions were used to effectively limit the scope of the task analyses by allowing focus on the most significant task parameters. Some assumptions were based on FAA and/or NASA direction and feedback, particularly from FAA spectrum engineering and FAA communications representatives, including the FAA FCS COCR development team. Task modeling assumptions included the following:

- UAS ATC communications services were assumed to be as defined in the COCR for A/G services. The task scope included both data and voice services.
- The task estimated control and ATC communications (C&C) bandwidth requirements for new UAS radio facility to UA links only; it was assumed that COCR defined ATC communications capacity requirements already accommodate ATC to UA links.

- The task did not include UAS Sense and Avoid related communications links (e.g., radar, optical, video, etc.) or UAS payload-related communications.
- The task focused on long term bandwidth requirements for UAS approximately through 2030.
- Potential aircraft or ground co-site interference issues were not considered.

1.4.2 Communications Architecture Assumptions

As stated above, several alternative architectures are possible for providing both control and ATC communications connectivity. Some of these alternatives have been explored by the C&C Working Group of RTCA SC–203. Because of its focus on supporting WRC preparation activities, this task was based on the concept that both control and ATC communications will be provided via a sectorized A/G LOS communications architecture, although control and ATC sector sizes and boundaries are not necessarily the same. This architecture is illustrated in Figure 6.

In this architecture UAS control sectors exist in parallel with existing ATC A/G radio sectors, as shown in the figure. In the figure the UAS sectors are shaded in color, while the ATC sectors are transparent. In each UAS control sector, a UAS radio control facility provides all communications connectivity between this facility and each UA within its sector. This connectivity is denoted by the blue arrows indicating ATC communications links, and by the green arrows for the control communications links. The light red arrows in the figure depict all the ATC radio facility to aircraft links, including both manned and unmanned aircraft. Each UA is controlled by a different pilot (i.e., pilot in charge—PIC), who may be remotely located from any of the UAS radio control facilities. Connectivity between UA pilots and UAS radio control stations is by terrestrial network connectivity, shown in light orange in the figure.

Since this architecture works solely by LOS A/G radio link connectivity, as the UAs transit the airspace, they will need to be "handed off" from one UAS radio control sector to another. This implies that the UA will break the RF link from one UAS radio control facility and establish a new link to a different UAS radio control facility in the newly entered UAS control sector. This is analogous to the situation for ATC communications, where every manned and unmanned aircraft pilot is handed off from

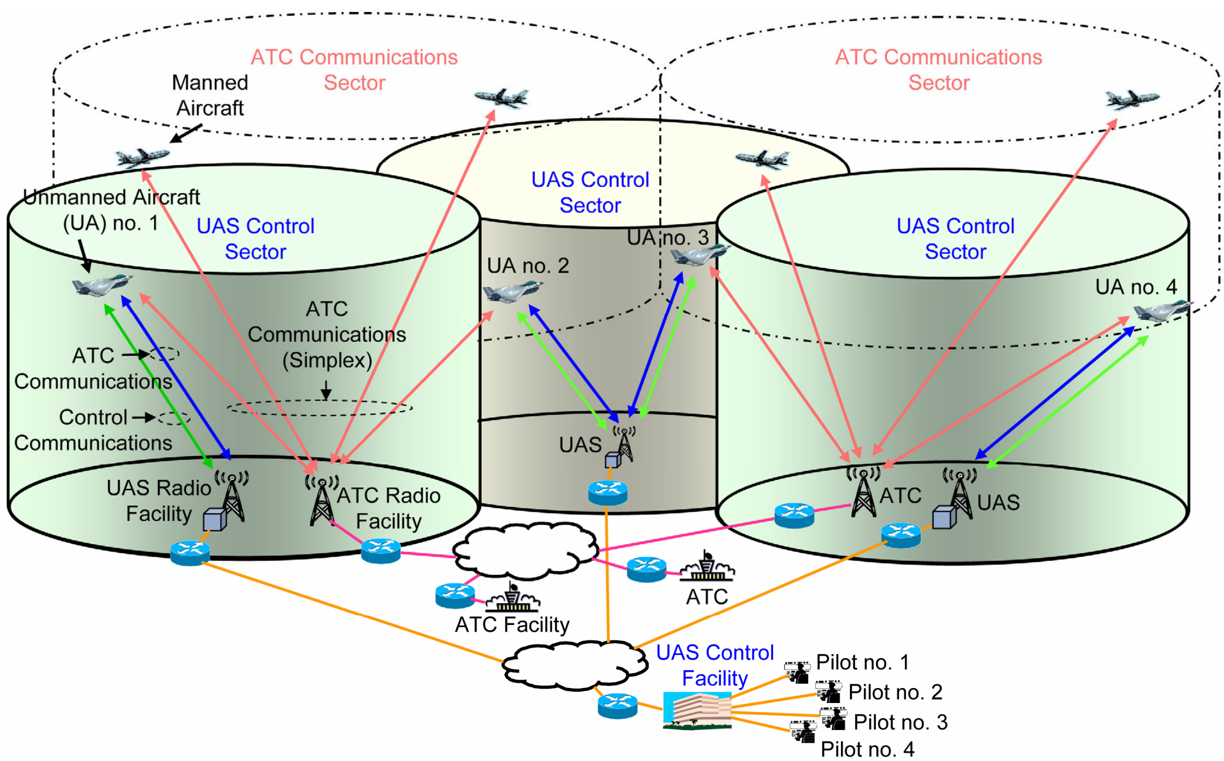


Figure 6.—UAS line-of-sight communications architecture assumed for the task.

the ATC controller in the sector being exited, to a new ATC controller in the new ATC sector being entered. Note that UAS control handoffs do not necessarily coincide with ATC controller handoffs. However, ATC controller handoffs for UAs should take place transparently to the ATC controllers, and it is probable that the ATC controllers will have information indicating the unmanned status of the aircraft.

Though the UAS control facility to UA control communications links should be fairly straightforward in implementation, the UAS control facility to UA ATC communications links represent the second link (or "hop") of the two-hop end-to-end connectivity necessary to connect ATC controllers to the PIC. This is sometimes referred to as a relay or "bent pipe" configuration, and usually relies on two radios connected "back-to-back" within the UA, shown as the blue and red boxes in Figure 7. The green box in the figure represents the transceiver required for the control communications link.

Figure 7 shows that up to seven separate links may be required to provide control communications and both voice and data ATC communications, including the following:

- One existing ATC radio facility to UA link: channel for ATC communications shared with all aircraft in sector shown in red (currently simplex very high frequency (VHF) DSB–AM)
- New UAS radio facility to UA links
  - Dedicated voice and data channels for ATC communications (uplinks and downlinks) shown in blue—Up to four links, depending on whether these are simplex or duplex
  - Dedicated channels for control communications (uplink and downlink) shown in green—Up to two links, depending on whether these are simplex or duplex

For the purposes of link efficiency and interference mitigation, it might be advisable to combine the ATC voice and data links. Furthermore, each of the uplink/downlink pairs might be implemented via simplex or full duplex links, potentially reducing the number of UAS radio facility to UA links to as few as two. This architecture decision is discussed further in section 2.6.1. In the limit, C&C message traffic could be combined and implemented via a single link, though this potential single point of failure configuration might present too much risk. For this task the control communications and ATC communications links were assumed to be implemented separately.

Other architecture-related assumptions for the control communications links are presented in section 2.4.2.1

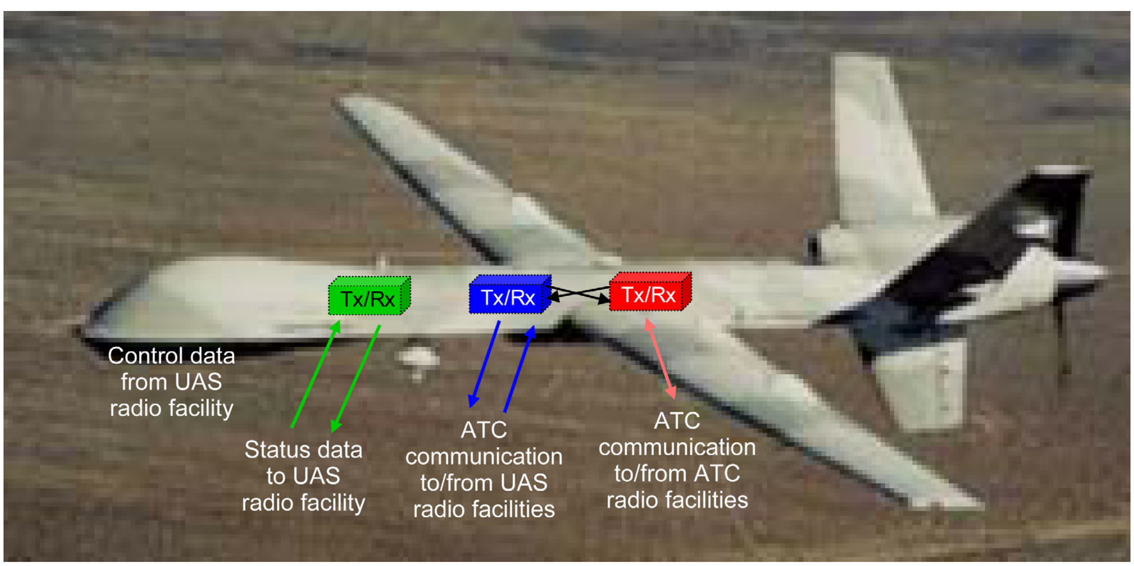


Figure 7.—UA communications relay links.

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2.0 Analysis

2.1 Introduction

This section describes the specific processes and findings for the analyses performed for each of the methodology steps described in the previous section.

2.2 UAS Specific Mission Types and Needs

As mentioned above, numerous RTCA SC–203 UAS mission scenarios were examined to identify UAS specific needs that might affect UAS communications requirements. Evaluation of these mission scenarios identified two main differences from traditional manned aircraft flight scenarios.

(1) A principal new paradigm typifying many proposed UAS missions is the need to "loiter" within particular airspace for periods from hours to months.
   a. Aside from the potential operational impact this has on ATC controller procedures, from the traffic modeling perspective it points to potentially heterogeneous flight durations and service instances (i.e., typical number of times a service is used within a service volume) for manned and unmanned aircraft.
   b. This impacts the COCR queuing model message arrival rate for ATC communications, which is inversely proportional to flight duration.

(2) A second major difference is the fact that many UAS missions will not traverse airports or the terminal maneuvering area (TMA) domains.
   a. This affects ATC communications flight durations and service instances for these domains.
   b. This does not affect control communications channel capacities, because the associated service volumes are assumed to not be part of the NAS. In any case, certain preflight command/status messages are required regardless of where the aircraft takes off.

An evaluation of the COCR traffic model led to the conclusion that the heterogeneous flight durations and message arrival statistics for manned and unmanned aircraft should not significantly affect the COCR ATS capacity requirements, which implicitly include UAS traffic. One reason for this assessment is that not all ATS service message types defined in the COCR have arrival statistics based on time; rather some only need to be sent under certain conditions, like entering or leaving a sector. Also, the fact that some UA will not traverse some NAS flight domains would probably have a second-order effect on the COCR flight statistics and data capacities because this would involve a small percentage of all UA in flight, which in turn would be a small percentage of all aircraft in flight. Thus, for this task, the COCR estimated per aircraft data capacities were used without modification.

2.3 UAS Aircraft Counts and Densities

2.3.1 UAS Aircraft Counts

As explained previously, UAS bandwidth requirements are dependent on projected UAS traffic densities and thus depend on estimates of the associated PIACs. This stage in the analysis involved conducting a search and evaluation of future projections of UA flying in the NAS. In contrast with the considerable information available on projected UAS systems to be acquired for military purposes, projected UAS estimates for operation in the NAS are not readily available and are highly speculative, probably because

- There are too many stakeholders, with broadly diverse potential uses and user categories, some of which have not yet been defined.
- Some projected commercial applications are proprietary and/or competition sensitive and therefore not widely disclosed.

- There are well-documented barriers to NAS operation that make it difficult to predict when and to what extent UAS will be allowed to operate. These include
  - Certification and regulatory issues
  - Current lack of appropriate standards
  - Lack of sufficient frequency spectrum
  - Safety concerns
  - Uncertain business cases

Despite the general dearth of UAS projections, two studies were located that provided some sense of the number of future UAS, based on the authors' assessments of the industry. Figure 8 and Figure 9 present two unmanned aircraft projections for several different time periods in the future.

An assessment of Figure 8 indicates that for the endpoint of the timeframe of interest for this study, 2030, the projected percentage of UA instrument flight rules (IFR) traffic would be greater than 3.9 percent and less than 38 percent. Since the projected growth curve looks to be nonlinear, rough order curve fitting to these few points shows that somewhere in the range of 5 to 10 percent of IFR traffic in 2030 could be unmanned.

Examination of Figure 9 reveals that the study author(s) believe that the number of civil unmanned aircraft in the 2015 timeframe would be smaller, but of the same order of magnitude as the number of jet transports and regional/commuter aircraft (i.e., in the thousands, as compared to the hundred of thousands of general aviation aircraft). Now it is reasonable to expect that UA flight operations would be more typical of these "working" aircraft than that of the general aviation class of aircraft. In other words, it might be expected that a significant percentage of UA in operation in 2015, would actually contribute to the PIAC. Looking further at the numbers, if, in the 2015 timeframe, the NAS PIAC is about two times

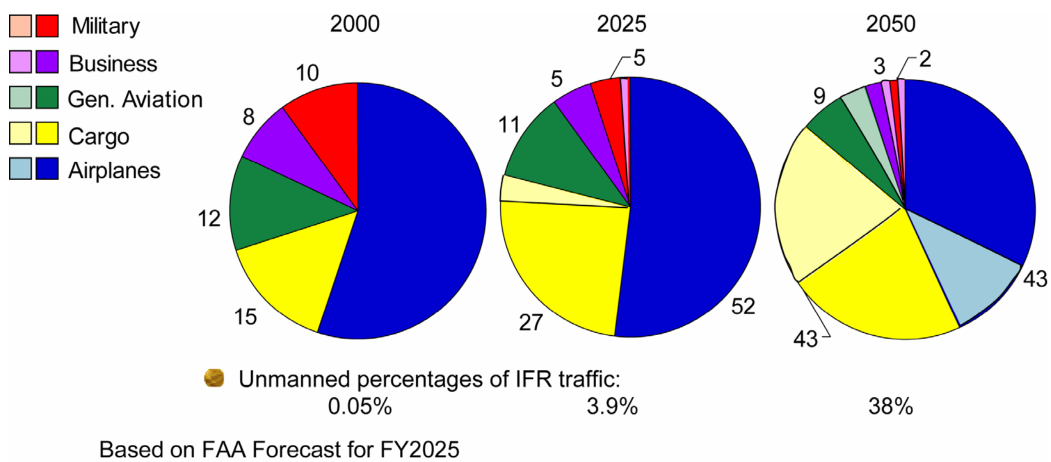

Figure 8.—Future projection of unmanned aircraft as a percentage of IFR traffic (ref. 5).

Manned aircraft[1]	
Jet transports	7 000
Regional/commuter	4 200
General aviation	230 800
Total manned aircraft	242 000
Civil UAVs in operation[2]	2 700
Civil UAVs per manned aircraft	0.1%

Notes:
[1] FAA long-range aerospace forecasts, FAA–APO–03–3 (June 2003)
[2] Does not include military UAVs operating in U.S. airspace

Figure 9.—Future projection of unmanned aircraft as a percentage of manned aircraft (ref. 6).

the approximately 5000 PIAC in the NAS today, this would yield a total PIAC of around 10 000. If 25 percent of the predicted 2700 operational civil UA were actually "working," that is, in flight, this would indicate that these 675 flying UA would contribute about 7 percent to the PIAC.

Based on these admittedly "back of the envelope" analyses, it was decided to select a range of 5 to 10 percent as the assumed percentage of UA flying in the NAS by the 2030 timeframe.

2.3.2 UAS Aircraft Densities

The COCR calculates aircraft densities for each of the flight domain service volumes it defines. A related Eurocontrol FCS investigation (ref. 4) defined several test service volumes for European airspace and estimated aircraft densities for these service volumes. The COCR and Eurocontrol service volume PIACs, physical volumes, and resulting aircraft density values are provided in Table III. Added to this data in the table are the associated UA densities corresponding to the two PIAC percentage values derived in section 2.3.1, namely 5 and 10 percent. These UA density numbers were used in later stages of the analysis to determine the number of UA per sector for the sector architecture defined in section 2.6.3.3.

Table III.—COCR and EUROCONTROL FCS service volumes

Service volume	Total PIAC	Volume, nmi^3	Total $aircraft/nmi^2$	UA density: $Aircraft/nmi^2$	
				5%	10%
COCR—NAS Airport HD Phase 1	200	---------	--------	---------	--------
COCR—NAS Airport LD Phase 1	12	---------	--------	---------	--------
COCR—NAS Airport HD Phase 2	290	---------	--------	---------	--------
COCR—NAS Airport LD Phase 2	19	---------	--------	---------	--------
COCR—NAS TMA LD Phase 1	14	3039	0.0046	0.0002	0.0005
COCR—NAS TMA HD Phase 1	16	2831	0.0057	0.0003	0.0006
COCR—NAS en route LD Phase 1	24	20,782	0.0012	0.0001	0.0001
COCR—NAS en route HD Phase 1	24	5119	0.0047	0.0002	0.0005
COCR—NAS TMA LD Phase 2	39	9240	0.0042	0.0002	0.0004
COCR—NAS TMA HD Phase 2	44	7691	0.0057	0.0003	0.0006
COCR—NAS en route LD Phase 2	59	33,388	0.0018	0.0001	0.0002
COCR—NAS en route HD Phase 2	45	10,132	0.0044	0.0002	0.0004
COCR—NAS en route super sector	95	31,996	0.0030	0.0001	0.0003
EUROCONTROL—TV1 Airport in flight	200	---------	--------	---------	--------
EUROCONTROL—TV1a Airport surface	264	---------	--------	---------	--------
EUROCONTROL—TV1 Airport in flight	26	259	0.1004	0.0050	0.0100
EUROCONTROL—TV2.1—TMA small	44	7691	0.0057	0.0003	0.0006
EUROCONTROL—TV2.2—TMA large	53	18,056	0.0029	0.0001	0.0003
EUROCONTROL—TV3.1—ENR small	28	10,132	0.0028	0.0001	0.0003
EUROCONTROL—TV3.2—ENR medium	62	33,739	0.0018	0.0001	0.0002
EUROCONTROL—TV3.3 ENR large	204	134,957	0.0015	0.0001	0.0002
EUROCONTROL—TV3.4 ENR super large	522	53,929	0.0010	0.00005	0.0001

2.4 UAS Message Statistics

2.4.1 UAS ATC Communications Message Statistics

As noted in section 2.2, UAS ATC communications service statistics and associated data capacity requirements were assumed to be identical to the manned aircraft ATS service statistics defined in the COCR. Table IV provides the per aircraft COCR A/G data capacity requirements for ATS services for each of the COCR defined flight domains, assuming the use of a separate channel for each aircraft. These numbers where used in later stages of the investigation to determine UAS ATC data communications bandwidth requirements.

Table IV.—COCR V1.0 A/G data capacity requirements, kpbs

Phase 2		APT SV dep	APT SV arr	TMA SV dep	TMA SV arr	ENR SV	OPR SV	AOA
Separate ATS	UL	6.9	1.8	5.6	3.8	5.7	5.7	6.7
	DL	6.2	1.9	6.8	1.6	6.7	8.5	12.5
	UL & DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

2.4.2 UAS Control Communications Message Statistics

During the review of the UAS scenarios developed by RTCA SC–203, it became apparent that the great diversity of UAS missions and variety of system and aircraft characteristics has resulted in many distinct and possibly proprietary communications link implementations. For this task, it was desirable to identify an accepted UAS standard that defines a standard architecture and specifies standard UAS message types, sizes, and quantities. Members of the UAS manufacturing community pointed to NATO STANAG 4586 (ref. 1) as an accepted generic standard for UAS message types and formats. Thus for this task, UAS message statistics for UAS control communications messages were based on implementation of STANAG 4586 compliant data link interface (DLI) messages.[3]

The following sections describe the development of the STANAG-4586-based UAS control communications messages statistics, including message instances, quantities, size, and calculated message data rates.

2.4.2.1 UAS Architecture Task Assumption

The STANAG 4586 standard architecture specifies that command and status messages must flow across the DLI between the vehicle-specific module (VSM) and the core UAV control system (CUCS), as shown in Figure 10. To allow STANAG 4586 compliant control stations to operate with legacy UA without STANAG 4586 compatibility built in, the standard accommodates the VSM residing either on the ground (for a legacy UA), as shown in the figure as Configuration A, or within a 4586-compliant UA, as shown as Configuration B. STANAG 4586 specifies that messages flowing across the DLI must include, in addition to a DLI "wrapper," network layer, transport layer, and security layer overhead. Because a VSM located on the ground, as in Configuration A, could strip out undesired network-related overhead data before RF transmission, this means that this A/G link might be able to transport significantly fewer bits per second (and require less bandwidth) than the A/G link in Configuration B, which has to carry the DLI required overhead. That is, there may be advantages to providing network connectivity to the UA. For this study, both configurations were considered for the major data rate driver, that is, for the command and status messages. For the less data-intensive message types, only statistics for Configuration B were calculated. Configuration A assumes a non-networked, native, or proprietary-type RF link with

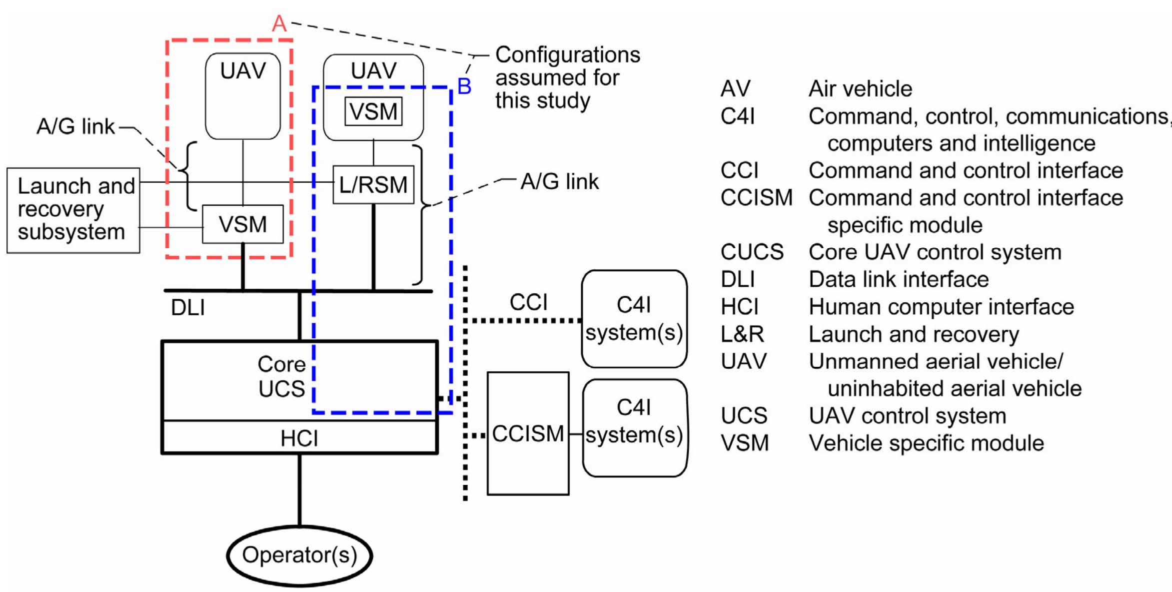

Figure 10.—Alternative VSM and the CUCS configurations.

[3]Information presented in RTCA SC–203 indicates that a newer STANAG that may possibly supersede STANAG 4586 is under development, but at the time of this study it is only in draft form.

some security overhead, while Configuration B implies an RF link that includes overhead for standards-based security and transport and/or network layer protocols.

2.5 UAS Control Message Quantities/Sizes

2.5.1 Introduction

In STANAG 4586, unmanned aircraft control and status messages fall into three general categories:

- Initialization, configuration, and mission upload messages exchanged preflight
  - Configuration messages also can be exchanged infrequently during flight as necessary if the operating mode or configuration of the aircraft is changed.
- Control messages sent to control the aircraft and its engines
  - The frequency of these messages is highly related to the level of autonomy characterizing the aircraft.
- Status messages sent (pushed) by the aircraft
  - These report dynamic changes in aircraft movements, direction, orientation, engine operation, etc.
  - These messages can be sent very frequently.
    - Typical update rates range from 1 to 20 times per second for critical parameters according to UAS manufacturers, where 1/s would be appropriate for a fully autonomous aircraft, and 20/s would apply to a hand flown UA.
    - These update rates are the major drivers in determination of aggregate aircraft to ground data rate, and hence bandwidth.

Specifically, this task included the following STANAG 4586 message types as part of its analysis:

- System identification (ID) messages
- Flight vehicle command and status messages
- Data link messages
  - Data link command and status messages
  - Data link transition messages
- Mission messages
- Subsystem status messages
- General configuration messages

As stated in the assumptions in section 1.4.1, payload data and payload control data were not included in the analysis, with the exception of a payload configuration message needed by the control system because of the payload's potential affect on flight dynamics.

Table V provides an example of STANAG 4586 defined system ID messages and flight vehicle command and status messages, and shows message length, and an assessment of the message "Class of Service" (CoS) for each of the messages listed. CoS is defined as follows: STANAG 4586 specifies allowable maximum transport delay between the human computer interface (HCI) and the DLI (see Figure 10). This serves a human factors purpose by ensuring that "human in the loop" (low autonomy) control systems operate with the low latency flight control and status messages (e.g., flight dynamics or heading information) necessary for remote control of unmanned aircraft.

Table V.—Example of STANAG 4586 messages

Message no.	Description	Push/pull	Source	Message length, bytes[a]	Class of service
System ID Messages					
1	CUCS authorization request	Push	CUCS	31	4
2–19	Reserved		CUCS	--	
20	Vehicle ID	Pull	VSM	73	3
21	VSM authorization response	Push/pull	VSM	31	4
22–39	Reserved		VSM	--	
40	Vehicle configuration command	Push	CUCS	20	5
41	Loiter configuration	Push	CUCS	42	
42	Vehicle operating mode command	Push	CUCS	17	5
43	Vehicle steering command	Push	CUCS	66	3
44	Air vehicle lights	Push	CUCS	18	3
45	Engine command	Push	CUCS	21	2
46	Flight termination command	Push	CUCS	18	2
47	Relative route/waypoint absolute reference message	Push	CUCS	61	2
48–99	Reserved	Push		--	3
Flight vehicle command and status messages					
100	Vehicle configuration	Pull	VSM	53	5
101	Inertial states	Push	VSM	84	3
102	Air and ground relative states	Push	VSM	64	3
103	Body-relative sensed states	Push	VSM	40	1
104	Vehicle operating states	Push/pull	VSM	145	32
105	Engine operating states	Push/pull	VSM	36	4
106	Vehicle operating mode report	Push/pull	VSM	17	2
107	Vehicle lights state	Push	VSM	18	4
108	Flight termination mode report	Push/pull	VSM	18	
109–199	Reserved		VSM	--	

[a]Does not include network/transport layer nor message wrapper overhead.

Though STANAG 4586 does not specify data link latencies, the HCI to DLI latency requirements indicate the relative criticality of the different messages. Therefore for this study, these latencies were translated into a CoS as shown in Table VI. The CoS help select relative message update rates for periodic messages, such as flight vehicle command and status messages. This is discussed in section 2.5.5.

Table VI.—STANAG 4586 HCI–DLI latency requirements mapped to a class of service

STANAG 4586 specified maximum latency, ms	Class of service
200	1
500	2
1000	3
2000	4
10,000	5

2.5.2 Message Overhead Assumptions

As recommended by STANAG 4586, messages for Configuration B included the following overhead:

- STANAG 4586 wrapper overhead: 34 bytes
- Network/transport layer overhead
  - STANAG 4586 recommends using Space Communications Protocol Standards (SCPS) to solve potential TCP/IP performance issues over the A/G wireless data link. Studies have shown that SCPS over IP is much more efficient than TCP/IP for wireless links. SCPS–TP over SCPS–NP seems to provide a marginal improvement over SCPS–TP/IP, though it is less clear.
  - For this study SCPS–TP/IPv6 overhead was assumed.

        - SCPS transport protocol (SCPS–TP) with user datagram protocol (UDP) messages: 8-byte header
        - IPv6: 40-byte header
- Security overhead
    - SCPS security protocol (SCPS–SP) with 14-byte overhead was assumed.
        - 2-byte header
        - 12-byte (96 bit) length integrity check value (ICV)
        - Key management overhead was not included

Messages for Configuration A were assumed to include 10 percent security overhead, and not include DLI wrapper, or transport/network layer overhead.

The following sections present the results of the analyses to determine appropriate UAS control configuration, mission upload, and flight vehicle command and status message statistics.

2.5.3 UAS Control Configuration Messages (Configuration B)

UAS control configuration messages are characterized by a two-way message exchange as the aircraft's operating parameters are initially configured during the preflight period. It was determined that the total amount of data exchanged is modest (see Table VII).

- Less than 15K bytes are sent from the control station to the UA
- Less than 25K bytes are sent from the UA to the control station

Several hundred bytes are also exchanged during each handoff from one UAS radio control station to another (not shown in table).

2.5.4 UAS Control Mission Upload Messages (Configuration B)

These are messages also exchanged during the preflight period, as the control station uploads mission information to the UA. During this time the UA periodically sends Upload Status messages. Typically, the UAS Control Mission Upload process requires relatively few bytes exchanged, as shown in Table VIII, which provides an example for a loitering-type mission.

2.5.5 UAS Flight Vehicle Command and Status Message Capacities

The exchange of UAS Flight Vehicle Command and Status messages includes the major driver of UAS data link capacities: UA status and telemetry messages. For the modeled UA to UAS control station downlink, a moderate level of autonomy was assumed, with critical parameter update rates ranging from 1 to 10 times per second (Hz) and varying among message type according to an assigned CoS. The mapping of CoS to update rate used for this analysis is shown in Table IX. Exceptions to the adopted method of mapping latencies to update rates are noted in the table.

Aggregated status/telemetry message data rate was found to be tens of thousands of bits per second—almost 29 kbps was estimated for Configuration B, as shown in Table X. The table also shows that the Configuration A (non-networked link) UA status/telemetry data rate estimate was around 11 kbps. Control message traffic was modeled as being periodic with fairly low update rates that are assumed to vary according to aircraft autonomy. For the low to medium autonomy case assumed in the analysis, average aggregate the UAS control station uplink command data rate was estimated to be around 5000 bps for Configuration B.

Table VII.—Calculated UAS control configuration message statistics (Configuration B)

CUCS originated								VSM originated							
	STANAG 4586 msg no.	No. of msg sent	Msg length	Msg length w/DLI wrapper	Msg length network/ transport layer overhead (bytes)	Msg length with security overhead (bytes)	Total DLI bytes		STANAG 4586 msg no.	No. of msg sent	Msg length	Msg length w/DLI wrapper	Msg length network/ transport layer overhead (bytes)	Msg length with security overhead (bytes)	Total DLI bytes
Field configuration request															
Excludes payload related message types, except 300	1200	97	35	69	117	131	12707								
Configuration complete	1203	1	28	62	110	124	124								
								Field configuration integer response	1300	7	146	180	228	242	1694
								Field configuration double response							
								Excludes payload related message types	1301	51	202	236	284	298	15198
								Field configuration enumerated response							
								Excludes payload related message types	1302	6	128	162	210	224	1344
								Field configuration command							
								Excludes payload related message types	1303	28	32	66	114	128	358
								Vehicle configuration	100	1	53	87	135	149	149
								Vehicle ID	20	1	73	107	155	169	169
								Data link configuration/assignment message	500	1	28	62	110	124	124
								Payload configuration							
								(Needed for vehicle assumes 2 payloads)	300	2	28	62	110	124	248
								Configuration complete	1203	1	28	62	110	124	124
CUCS configures user interface															
Data link assignment request	404	1	25	59	107	121	121								
								Data link configuration/assignment message	500	1	28	62	110	124	124
Data link set up message	400	1	33	67	115	129	129								
Pedestal configuration message	402	1	40	74	122	136	136								
Data link control command	401	1	25	59	107	121	121								
Pedestal control command	403	1	46	80	128	142	142								
								Data link control command status	502	1	24	58	106	120	120
								Data link status report	501	1	38	72	120	134	134
								Pedestal status report	503	1	58	92	140	154	154
Specified vehicle ID connection request															
CUCS authorization request															
CUCS requests control over a specific vehicle/vehicle type	1	1	13	65	113	127	127								
								VSM authorization response							
								VSM grants CUCS control over specified vehicle/vehicle type	21	1	31	65	113	127	127
CUCS configuration and command messages:															
CUCS controls the AV/payload at specified LOI															
Display unit request	1201	1	25	59	107	121	121								
CUCS resource report	1202	1	34	68	116	130	130								
Vehicle configuration command	40	1	20	54	102	116	116								
Vehicle operating mode command	42	1	17	51	99	113	113								
Loiter configuration	41	1	42	76	124	138	138								
Vehicle steering command	43	1	66	100	148	162	162								
Air vehicle lights	44	1	18	52	100	114	114								
Relative route/waypoint absolute reference message	47	1	61	95	143	157	157								
Configuration complete	1203	1	28	62	110	124	124								
								VSM status message/configuration updates							
								Vehicle operating mode report	106	1	7	51	99	113	113
								Vehicle operating mode report configuration complete	1203	1	28	62	110	124	124
Number of bytes associated with initial connection and configuration			**Total bytes from control station**				**14,782**					**Total bytes from aircraft**		**23,530**	

Table VIII.—Calculated UAS control mission upload message statistics (Configuration B)

Functions		CUCS (control stations) originated: STANAG 4586 msg no.	No. of msg sent	Msg length	Msg length w/DLI wrapper	Msg length network/ transport layer overhead (bytes)	Msg length with security overhead (bytes)	Total DLI bytes		VSM (aircraft) originated: STANAG 4586 msg no.	No. of msg sent	Msg length	Msg length w/DLI wrapper	Msg length network/ transport layer overhead (bytes)	Msg length with security overhead (bytes)	Total DLI bytes
Point-to-point mission																
Mission related	Messages no. 800 to 900 ref. Vol 1: STANAG 4586 Implementation Guidelines 3.4.3.2.6 mission messages This sequence assumes ground VSM with message 800 to convert and transmit to AV in native format															
Mission plan upload Msg 802 to 806 sequence for each waypoint																
	AV position waypoint	802	10	60	94	142	156	1560								
	AV loiter waypoint	803	0	38	72	120	134	0								
	Payload action waypoint	804	0	58	92	140	154	0								
	Airframe action waypoint	805	5	20	54	102	116	580								
	Vehicle specific waypoint	806	5	39	73	121	135	675								
	Assumed no. waypoints	10														
	AV route	801	1	39	73	121	135	135								
	Mission upload command	800	10	39	73	121	135	1350								
									Mission upload/download status	900	2	18	52	100	114	228
									Assumed no. updates	2						
				Total bytes from control station				**4165**				**Total bytes from aircraft**				**228**

Table IX.—Update rate assignments for UA status/telemetry messages

Message	Message number	STANAG 4586 specified HCI–DLI latency, ms	Mapped class of service, CoS	Assigned update rate, Hz	Remarks
Inertial states	101	1000	3	2	
Air and ground relative states	102	1000	3	2	
Body-relative sensed states	103	200	1	10	
Vehicle	104	1000	3	2	
Operating states					
Engine operating states	105	500	2	5	
Vehicle light states	107	500	2	1	Took exception to CoS assignment; did not agree vehicle light state should be a low latency item.
Data link status report	501	1000	3	1	Took exception to CoS assignment; thought data link status was more critical.
Pedestal status report	503	2000	4	0.2	Took exception to CoS assignment; did not agree pedestal status should be a low latency item. Do not believe that pedestals can move very fast.
Subsystem status report	1101	1000	5	1	Took exception to CoS assignment; thought subsystem status was more critical.

Table X.—Calculated UAS flight vehicle command and status message statistics

CUCS (ground) originated										
	STANAG 4586 msg no	Aperiodic: no. of msg sent per phase of flight	Periodic msg rate no./s	Msg length (bytes)	Msg length w/DLI wrapper (bytes)	Msg length network/ transport layer overhead (bytes)	Msg length with security overhead (bytes)	Aperiodic: total bytes per phase of flight	Periodic bits/s	Periodic bits/s w/o transport network overhead
Vehicle steering command	43	--	0.2	66	100	148	162	0	259.2	116.2
Engine command	45	--	0.1	21	55	103	117	0	93.6	18.5
Subsystem status request	1000	--	5	20	54	102	116	0	4640	880.0
Subsystem status detail request	1001	1	---	20	54	102	116	116	0	0.0
				404	1	25	59	107	121	121
Aggregate data rate from control station, bps							**B 4993 networked**		**1015 A non-networked**	

VSM (aircraft) originated										
	STANAG 4586 msg no.	Aperiodic: no. of msg sent per phase of flight	Periodic msg rate no. s	Msg length, bytes	Msg length w/DLI wrapper, bytes	Msg length network/ transport layer overhead, bytes	Msg length with security overhead, bytes	Aperiodic: total bytes per phase of flight	Periodic bits/s	Periodic bits/s w/o transport network overhead
Inertial states	101	--	2	84	118	166	180	0	2280	1478.4
Air and ground relative states	102	--	2	64	98	146	160	0	2560	1126.4
Body-relative sensed states	103	--	10	40	74	422	136	0	10880	3520.0
Vehicle operating states	104	--	2	145	179	227	241	0	3856	2552.0
Engine operating states	105	--	5	36	70	118	132	0	5280	1584.0
Vehicle light status	107	--	1	36	70	118	132	0	1056	316.8
Data link status report	501	--	1	38	72	120	134	0	1072	334.4
Pedestal status report	503	--	0.2	58	92	140	154	0	246.4	102.1
Subsystem status report	1101	--	1	22	56	104	118	0	944	193.6
Subsystem status alert message	1100	1	---	107	141	189	203	203	0	0.0
Aggregate data rate from aircraft, bps							**B 28,774 networked**			**11,208 A non-networked**

2.6 Estimating UAS C&C Bandwidth Requirements

The preceding sections presented the methods and results of the analyses performed to estimate: (1) projected future UA PIACs and densities and (2) the UAS control and ATC communications data rates necessary to transfer messages between a UAS control station and a low to medium autonomy UA. The goal for this task was to determine the required channel bandwidth for the links shown in Figure 11 necessary to provide the required data rates to all the UA flying in the NAS as characterized by the projected UA densities. The methodology used to accomplish this goal is shown in Figure 12.

The process began by selecting appropriate channel access approaches for the control and ATC communications links to provide the desired link connectivity (see Figure 11). It should be noted that this step was taken only so far as to allow the desired estimation process be performed. In other words, this step made some reasonable “design” decisions; however, identifying the best or most efficient design or technology was beyond the scope of this task. Specific design decisions included determination of the need for simplex or duplex channels, which helped drive the sector architecture definition step; and whether dedicated or shared channel resources are needed.

The next step was the definition of an appropriate sector architecture to help define certain important system parameters such as required slant range (to allow calculation of path loss in the link budgets), and to help to determine how many communications channels would be necessary per sector, based on the assumed UA densities. This step included exercise of certain constraints to ensure required sector coverage and to avoid co-channel interference.

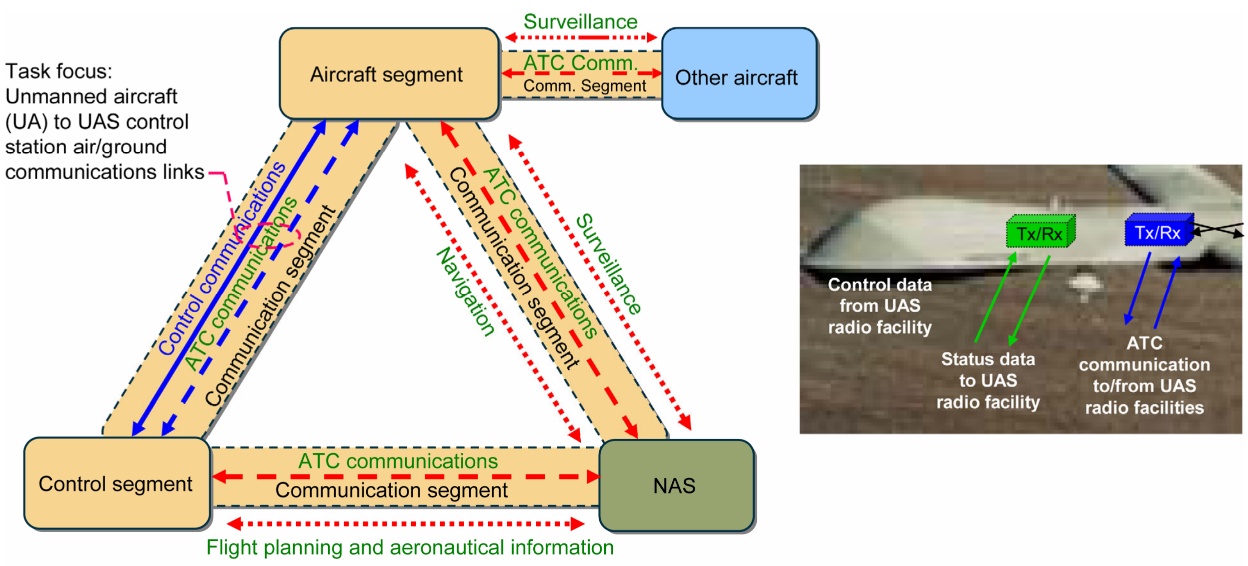

Figure 11.—UAS A/G radio links of interest for this task.

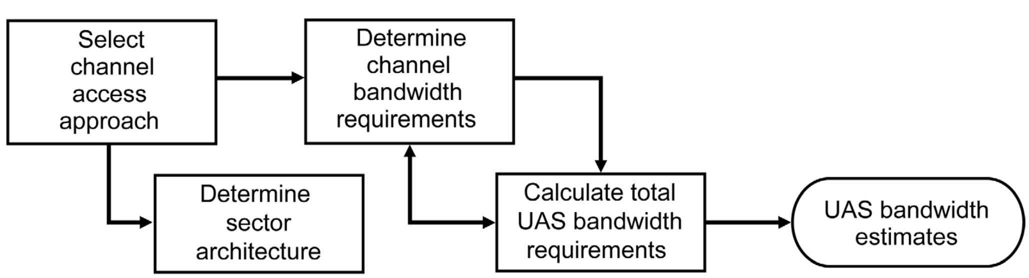

Figure 12.—Methodology for developing UAS C&C bandwidth estimates.

The step of determining the channel bandwidth requirements involved making a design decision concerning suitable modulation types and determining how much FEC coding would be needed to provide the required link performance. The principal tool for this step was link budget analysis to evaluate bandwidth and power tradeoffs. The principal output of this step was the required channel bandwidth for each of the identified control and ATC communications links.

Given the required channel bandwidth per link and the calculated number of links necessary to provide complete coverage, as determined by the sector architecture, the total aggregate required bandwidth for each of the defined links was estimated. During the course of this task it was clearly apparent that the total estimated aggregate required bandwidth was greatly influenced by a few specific modeling assumptions and design decisions. For this last step of the analysis, this sensitivity was briefly analyzed and graphically illustrated to show its effect.

The following sections describe the methodology and results in more detail.

2.6.1 Channel Access Approach

2.6.1.1 UAS Control Communications

As shown in section 2.5.5, UAS control communications message capacity estimates are driven by nominally constant rate command messages uplinked to the UA and status/telemetry messages downlinked from the UA. This high, continuous demand for the channel points to the need for dedicated full duplex channels for each ground station to UA link. Dedicated channels are needed because contention-based protocols could not efficiently provide sufficient quality of service (QoS) in terms of latency and availability. There is no queuing possible because the message arrival rates are constant and deterministic for each user. Full duplex channels are needed for the same reason. Dedicated bandwidth can be provided by frequency division multiple access (FDMA), time division multiple access (TDMA), or code division multiple access (CDMA) approaches; each has its advantages and disadvantages, some of which are listed in Table XI.[4]

Table XI.—UAS control communications access type high-level comparison

Access type	Complexity	UA power and bandwidth demands
FDMA	Low	Low
TDMA	Medium	High
CDMA	High	High

Based on this high-level comparison, an FDMA system consisting of one set of asymmetrical dedicated full duplex channels per ground station to UA link was assumed to be best and most straightforward for bandwidth estimation purposes. Asymmetrical channels are needed because the downlink (status and/or telemetry) capacity requirements are greater than the uplink (command) capacity requirements.

2.6.1.2 ATC Communications

The UA to UAS control facility link is analogous to the hard wired circuit that connects a manned aircraft pilot with an aircraft radio. On a manned aircraft this is a dedicated high-availability, low-latency "link."

In the UAS case this link could be provided either by a shared link or a dedicated link, each with its own advantages and disadvantages. Table XII presents a simple comparison of these two approaches. As with the control communications link case, an FDMA system consisting of two dedicated fixed rate

[4]One factor not considered in the table has to do with propagation issues, specifically the bandwidth of the signal (or equivalently, the symbol duration) in relation to the frequency dependence of the propagation channel. Using low bit rate FDMA signals in the typical aeronautical A/G radio channel will tend to reduce the effects of delay spread and the associated intersymbol interference (i.e., ensure "flat fading" channel conditions).

duplex channel pairs per ground station to UA link (voice and data) was assumed for bandwidth estimation purposes.

It should be noted that for implementation, voice and data traffic could be multiplexed, resulting in one duplex ATC communications uplink and downlink channel pair. This could have some advantages in cost and simplicity; reduction of interference issues (fewer links means fewer opportunities for interference); and even potentially provide some bandwidth efficiencies due to the statistical nature of ATC communications. Further consideration of this option was beyond the scope of this study.

Table XII.—UAS ATC communications access type high-level comparison

Access	Advantages	Disadvantages
Dedicated	• Minimum latency • Predictable availability • Simpler • Possible to use nonaviation standard technologies (P25)	• Bandwidth intensive • No current ICAO standard
Shared	• Minimum potential bandwidth impact • Possible use of existing ICAO standard (VDL–M3)	• More complex • Availability issue—channel contention for two links rather than for one link • Existing standards like VDL–M3 might not work without modifications, which should have to be standardized

2.6.2 Channel Bandwidth Requirements

2.6.2.1 UAS C&C Link Budgets

Communications link budgets are typically used to perform power-bandwidth tradeoffs for links and were developed in this study to determine appropriate channel bandwidths. Key link budget parameters for this task included the following:

- Range between the UA and the UAS ground station, which was determined by the sector architecture
- Required received E_b/N_0 performance, which is dependent on modulation type and FEC coding (if any)
- Frequency band—aeronautical bands were considered
- Receive system noise temperature, which is dependent on external noise, line losses, and front end (receiver or low noise amplifier) noise figure
- Antenna gains—based on aeronautical standards

Selected UAS control and ATC communications link parameters used for this task are discussed in the following sections.

2.6.2.2 Selected UAS Control Communications Link Parameters

The next few sections describe the specific link parameter design decisions made for the UAS control communications links, including modulation and FEC coding selection, frequency band, system noise temperature, and antenna gains.

2.6.2.2.1 UAS Control Communications Modulation Types

Existing UAS often use aeronautical telemetry standard constant envelope[5] modulations such as narrow band frequency modulation (FM), some type of continuous phase modulation (CPM), or other interoperable modulation types for LOS control/status/telemetry links, including

[5]Constant envelope modulations provide good performance with the less expensive and simpler, nonlinear amplifiers often used in transmitters for aeronautical and spacecraft applications. In particular, constant envelope modulations resist spectral spreading, which can cause adjacent channel interference typical of nonlinear amplifiers. Please note that the SRRC OQPSK modulation selected as the notional modulation for this study is not a constant

- Variants of shaped offset QPSK (SOQPSK)
- Variants of Feher patented QPSK (FQPSK)

The Consultative Committee for Space Data Systems (CCSDS) has standardized similar bandwidth efficient modulations for space telemetry applications, which include, in addition to the two modulations just listed:

- Gaussian minimum shift keying (GMSK)—a type of CPM
- Filtered OQPSK modulations (aside from SOQPSK), such as square root raised cosine (SRRC) OQPSK
- 4D–8PSK–Trellis coded modulation (TCM)

The telemetry standard modulations are fairly bandwidth efficient and, when employed with suitable FEC coding, provide excellent E_b/N_0 performance. A summary of the bandwidth efficiencies and performance of these modulation types is shown in Table XIII.

Square root raised cosine (SRRC) filtered (α = 0.5) OQPSK was selected as the notional modulation used in the link budgets, as it combines good E_b/N_0 performance with good interference susceptibility performance. Figure 13 illustrates the channel efficiency of this particular modulation. It should be noted that R_s used in the figure is the coded symbol rate, that is, it represents the bit rate after the FEC encoder, not the channel symbol rate after the modulator.

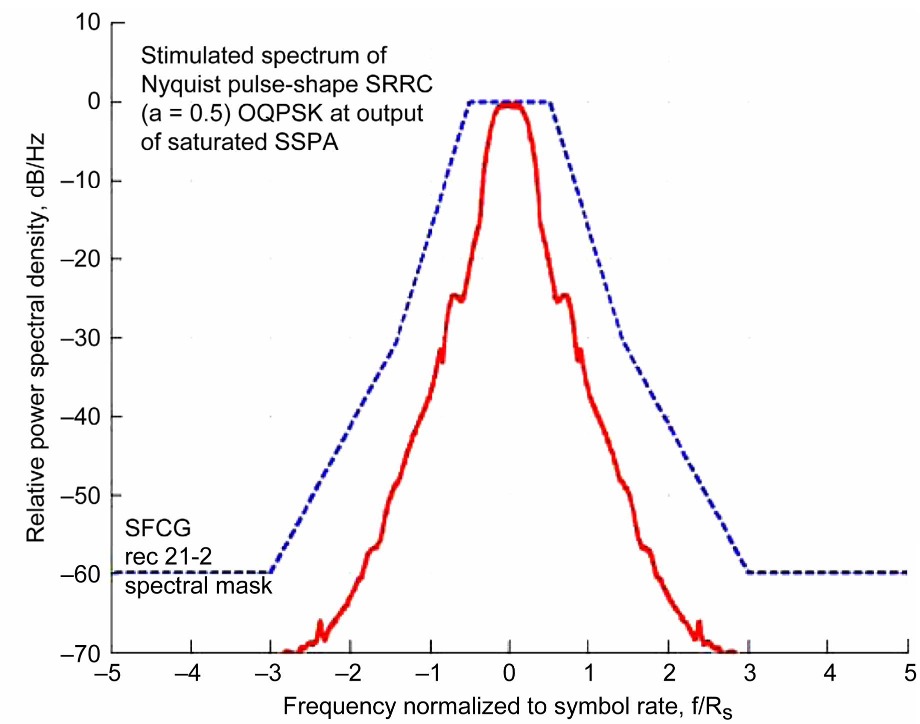

Figure 13.—Spectrum of suitable modulation type for UAS control communications.

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envelope modulation; however, the effect of nonlinear amplifier spectral spreading has been included in the spectral efficiency value presented below.

Table XIII.—Performance of potential UAS control communications modulation types (ref. 6)

Modulation type	Two-sided –60 dB bandwidth	Occupied bandwidth
Unfiltered BPSK[a]	635 R_S	20.56 R_S
Baseband filtered OQPSK/PM		
Butterworth 6th order	2.70 R_S	0.88 R_S
SSRC α = 0.5	2.68 R_S	0.88 R_S
Bessel 6th order	3.69 R_S	0.93 R_S
Baseband filtered OQPSK I/Q		
Butterworth 6th order	4.06 R_S	0.86 R_S
SSRC α = 0.5	4.24 R_S	0.88 R_S
Bessel 6th order	4.95 R_S	1.34 R_S
Precoded GMSK BTs=0.25	2.14 R_S	0.86 R_S
SOQPSK		
Version A	1.94 R_S	0.77 R_S
Version B	2.06 R_S	0.83 R_S
FQPSK-B	2.18 R_S	0.78 R_S
Occupied bandwidth recommended efficient modulations after spectral regrowth due to saturated SSPA. Please note that RS is the coded symbol rate, that is, after the FEC encoder, not the channel symbol rate after the modulator.		

Modulation type	Receiver type	E_b/N_0 for 10^{-6} BER	CCSDS yellow book reference
Unfiltered BPSK (reference only)	Integrate and dump	2.55 dB	1–06, 1–14
Baseband filtered OQPSK/PM			
Butterworth 6th order	Integrate and dump	3.09 dB	N/A
SRRC α = 0.5		3.16 dB	
Baseband filtered OQPSK I/Q			
Butterworth 3rd order	Integrate and dump	2.91 dB	1–06, 1–14
Butterworth 6th order		3.04 dB	
SRRC α = 0.5		3.06 dB	
Pulse-shaped SRRC α = 0.5	Matched filter	2.77 dB	
Shaped offset QPSK			
Version A	Integrate and dump	3.74 dB	N/A
Version B		3.46 dB	
Precoded GMSK BT_s = 0.25	Quasi-matched filter + 3 tap equalizer	2.73 dB	1–06, 1–14
FQPSK-B	Quasi-matched filter + 3 tap equalizer	2.88 dB	1–4
Simulated BER of selected bandwidth-efficient modulations using the CCSDS standard rate, ½, k=7 convolutional inner code concatenated with a (225, 223) Reed-Solomon outer code.			

[a]Constant envelope modulations provide good performance with the less expensive and simpler, nonlinear amplifiers often used in transmitters for aeronautical and spacecraft applications. In particular, constant envelope modulations resist spectral spreading, which can cause adjacent channel interference typical of nonlinear amplifiers. Please note that the SRRC OQPSK modulation selected as the notional modulation for this study is not a constant envelope modulation; however the effect of nonlinear amplifier spectral spreading has been included in the spectral efficiency value presented below.

The link budget parameters relating to modulation performance and FEC coding selection included the following:

- Spectral efficiency at 99 percent bandwidth (occupied bandwidth[6]) = [7]0.88R_s
- Required bit error rate (BER)[8] = 10^{-6}

[6]Occupied bandwidth is defined by article 1.153 of the ITU Radio Regulations (ITU RR) as the width of a frequency band such that, below and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage β/2 of the total mean power of a given emission, where β is taken to be 1 percent. For β = 1 percent; this is often referred to as the 99 percent power containment bandwidth.
[7]This value includes the slight spectral spreading due to nonlinear amplification in the transmitter.
[8]Selection of this value is discussed in section 2.6.4.

Table XIV lists the range of FEC coding schemes and the associated required E_b/N_0 performance for the selected modulation (SRRC OQPSK) used for the link analyses to determine the control and ATC communications channel bandwidths.

Table XIV.—Theoretical performance of example modulation with different levels of FEC coding

Link FEC coding	Theoretical E_b/N_0, dB
Uncoded	11.5
¾ Conv. FEC only	6.5
CC RS+¾ Conv. FEC	4.5
½ Conv. FEC only	5.0
CC RS+½Conv. FEC	3.0

2.6.2.2.2 Other Selected UAS Control Communications Link Parameters

UAS control communications link budgets were based on an implementation in the aeronautical "L-band," that is 960 to 1215 MHz.[9] This yields a 2-dB range in free space path loss across this band. A frequency of 1088 MHz (center of band) was used in the link budgets for path loss.

For the determination of system noise temperature (see Figure 14), line loss values consistent with typical aeronautical application link budgets were assumed. These were 3-dB transmit line losses for the UA, and 2-dB receive line losses for the UAS radio control facility. In addition, system noise temperature was dependent on a conservative 100K external noise assumption, and an 8-dB receiver noise figure (also conservative) for the UAS radio control facility.

Antenna gains assumed for the link budget analysis were as follows. The task assumed a 6-dBi gain for the ground system antenna consistent with typical aeronautical application link budgets, and a 0-dBi gain for the UA antenna consistent with antenna gains specified for aircraft antennas in the universal access transceiver (UAT) MOPS (ref. 7). The operational frequencies for the UAT antennas are similar to the frequency range (L-band) assumed for this study.

The ATC voice communications channel was assumed to carry 4800 bps vocoded data; the same modulation and FEC coding parameters used for the control communications links were applied for the ATC voice communications link analysis. In addition, duplex (separate uplink and downlink) channels were assumed because they might be necessitated by the end-to-end latency issues with vocoded speech in two directions and the burden of two "hops."

For ATC data communications the same filtered SRRC OQPSK modulation and range of FEC coding was used as for the other links. Just as in the case with control communications and ATC voice communications, duplex (separate uplink and downlink) channels were assumed for ATC data channels.

Table XVII indicates which data capacity values were used in the ATC data communications link analyses, based on the similarities to the associated components of the sector architecture defined for this task. In the case of the airport and TMA domains, the larger of the two data capacity values for each flight domain were selected for sizing the UA to UAS ground radio facility ATC data communications links. Please note that selecting the data capacity requirements associated with the autonomous operations area (AOA) provided a conservative upper bound for the larger, higher altitude service volumes.

[9]Please note that International Civil Aviation Organization (ICAO) is presently considering spectrum from 960 to 1024 MHz for the Future Radio System.

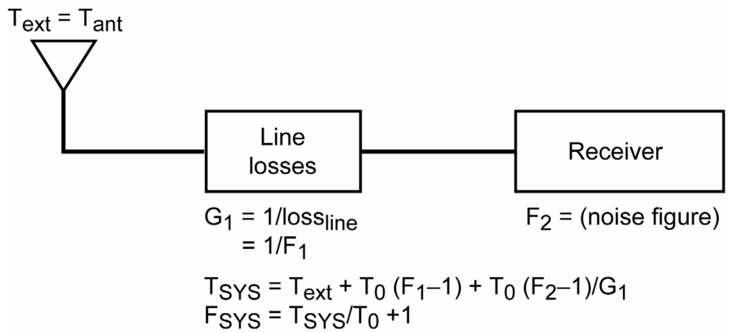


Figure 14.—Calculating system noise temperature and noise figure.

Table XV.—COCR V1.0 A/G data capacity requirements, kpbs

Phase 2		APT SV Dep	APT SV Arr	TMA SV Dep	TMA SV Arr	ENR SV	ORP SV	AOA
Separate ATS	UL	**6.9**	1.8	**5.6**	3.8	5.7	5.7	**6.7**
	DL	**6.2**	1.9	**6.8**	1.6	6.7	8.5	**12.5**
	UL & DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

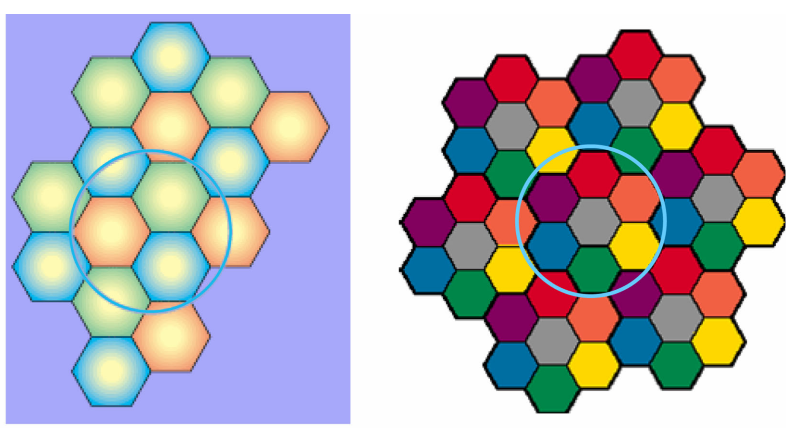
2.6.3 Sector Architecture

Consistent with standard telecommunications practice, the sector architecture for this task was defined using hexagonal tiling. In this approach, each hexagonal sector provides a given number of separate channels to serve the expected maximum number of users in that sector. All available frequencies are allocated and reused in repeating clusters of sectors of size N. N, the reuse factor, can only take on values according to the following relation: $N = i^2 + ij + j^2$, where i and j are nonnegative integers (ref. 8). Figure 15 provides some examples of different reuse patterns. In each example, the colored hexagons represent sectors with the same set of frequencies, that is, "co-channel" sectors. The normalized distance between co-channel sectors is found to be (ref. 8):

$$Q = D/R \sqrt{\left(i^2 + ij + j^2\right)} = \sqrt{(3N)}$$

where

R = radius of the sector (cell)
D = distance to the center of the nearest co-channel sector



Reuse = 3 Reuse = 7

Figure 15.—Examples of different reuse patterns.

The selection of N is based in part on the co-channel protection required for the particular cellular telecommunications application. Increasing the value for N will increase the co-channel interference protection for the nearest co-channel sectors. The tradeoff in increasing N is the fact that, for a given number of frequencies required per sector, it increases the total number of frequencies required for the system.

It should be noted that the co-channel interference discussion to follow is based on the full duplex channel design decisions stated section 2.6.1. In contrast with the typical aeronautical A/G radio interference scenario based on simplex channels (such as the VHF A/G ATC radio channel case), in the full duplex channel case, co-channel interference considerations do not include aircraft to aircraft interference issues that usually drive the derivation of required reuse distance.

If it can be assumed that most of the co-channel interference into an individual sector comes from the six closest sectors (see Figure 17), and assuming (1) all the transmitting stations are equidistant from the victim sector and (2) each of the interfering transmitter transmits with the same power, then the signal to interference ratio (S/I) can be approximated as (ref. 8):

$$S/I = R^{-n} \Big/ \sum D_i^{-n} = \left[\sqrt{(3N)}\right]^n \Big/ 6$$

where

n = path loss exponent, typically around 2 for A/G radio channels

D_i = distance between the sector and the *i* interfering transmitters, assumed to be 6 in this case

Table XVI provides the estimated S/I for several values of reuse factor for path loss exponent values n = 2, 3, and 4. As shown in the table, the values for n = 2 (assumed for the A/G channel) point to the need in many cases to choose a fairly high reuse factor, that is, fairly large spacing between co-channel sectors to provide reasonable co-channel interference protection.

Table XVI.—S/I versus reuse factor for different path loss exponents

N	S/I (dB) n = 2	S/I (dB) n = 3	S/I (dB) n = 4
1	–3.0	–0.6	1.8
3	1.8	6.5	11.3
4	3.0	8.4	13.8
7	5.4	12.1	18.7
9	6.5	13.7	20.8
12	7.8	15.6	23.3
13	8.1	16.1	24.0
16	9.0	17.4	25.8
19	9.8	18.6	27.3
21	10.2	19.2	28.2
25	11.0	20.3	29.7
27	11.3	20.8	30.4
28	11.5	21.1	30.7

For the cell sizes and distances typically considered for cellular telecommunications, co-channel interference is not usually limited by the curvature of the Earth; however, for A/G communications interference can be mitigated by the curvature of the Earth. For aircraft communicating with a ground station, radio line of sight (RLOS) can be calculated as RLOS (nmi) = $1.23 \times \sqrt{(h_1 + h_2)}$ (ref. 9), where h_1 is height in ft of the aircraft and h_2 is the height in feet of the ground station antenna (4/3 Earth effective radius assumption), see Figure 16. What this means is that sector sizes can be selected so that co-channel sectors are beyond LOS from each other, in which case S/I becomes high enough to have negligible effect on system performance.[10]

[10]Tropospheric ducting can be a source of interference that might impact UAS communications in some cases. It is not considered in this study, but should be investigated in the context of a detailed UAS communications design and development.

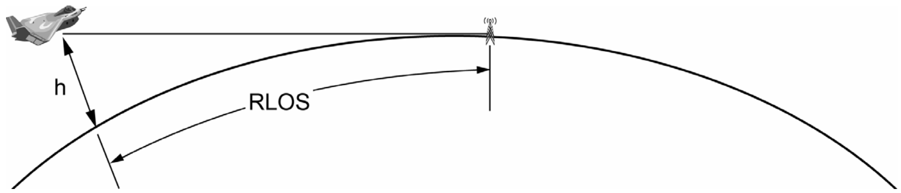


Figure 16.—Definition of radio line of sight.

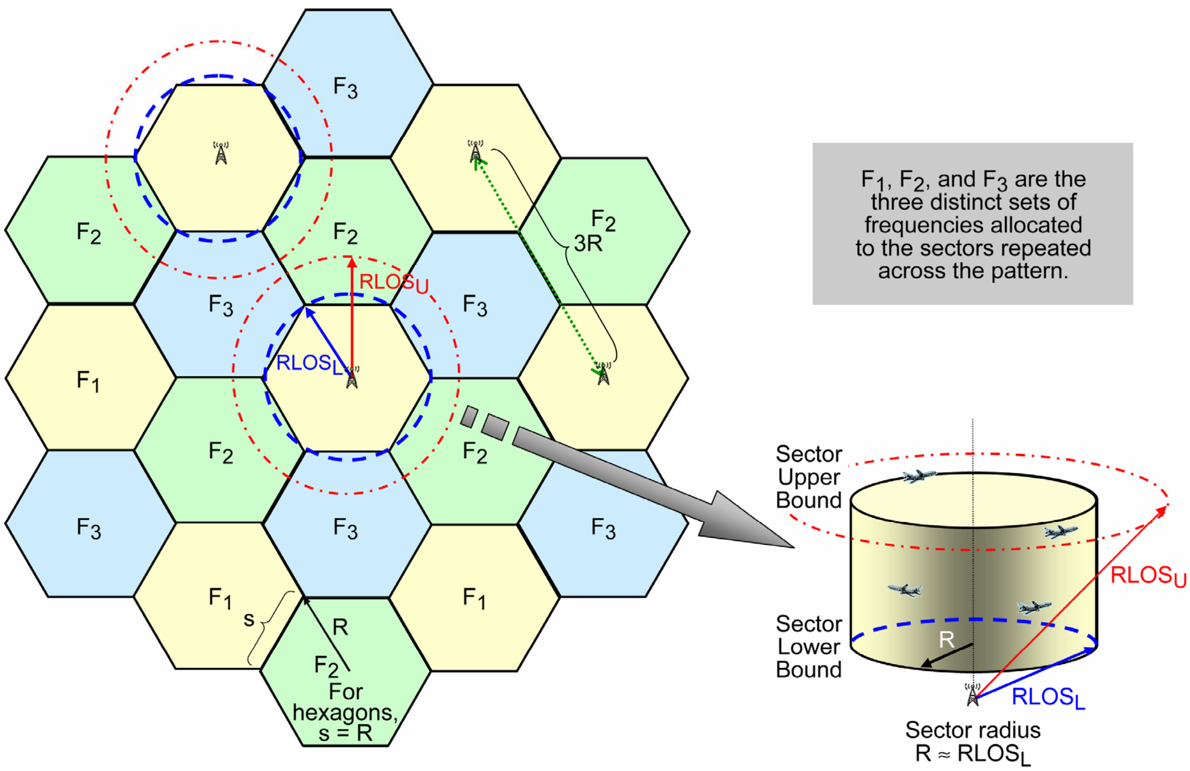


Figure 17.—Sector architecture example cluster size (Reuse) N = 3.

Figure 17 provides an example of a sector architecture for N = 3. The figure illustrates the frequency reuse pattern, and illustrates the fact that if the RLOS at the sector lower boundary is approximately equal to the sector radius, then the RLOS at the upper boundary of the three dimensional sector necessarily exceeds the sector radius. This impacts selection of the sector dimensions, as explained in the next section.

2.6.3.1 Sector Architecture Constraints

In defining candidate sector architecture, and given the full duplex channel design decision adopted for this study, two constraints come into play (see also Figure 19):

- To assure coverage $R < RLOS_{Lower}$, where
  - R is the sector radius, and
  - $RLOS_{Lower}$ is the radio line of sight of the lower boundary of the sector.
    - For sectors with a lower boundary at ground level, this condition is satisfied through typical ground station antenna heights and take-off/landing aircraft altitudes; for example, at 1000 ft, RLOS = 39 mi.
- To avoid co-channel interference (for duplex channels) $RLOS_{Upper}/R < (Q - 1)$, where
  - $RLOS_{Upper}$ is the radio line of sight of the upper boundary of the sector
  - Q is the co-channel reuse distance = $\sqrt{(3N)}$, as defined above

Figure 18 shows the sector reuse factor as a function of $RLOS_{Upper}/R$ required to provide co-channel interference protection due to LOS coverage limitations. Please note that for values of $RLOS_{Upper}/R$ on the blue curve, the next highest value of N must be selected. For example, for $RLOS_{Upper}/R = 3$, since the value on the curve is about 5.2, a value of N = 7 must be selected. Conversely, if a reuse factor of 3 was desired, then $RLOS_{Upper}/R$ must be less than 2 to avoid co-channel interference.

The two constraints provided above were used to define suitable sector architectures to permit the estimation of total UAS control and ATC communications bandwidth requirements. Figure 19 illustrates the approach for a desired reuse factor of 3.

2.6.3.2 Multilevel Sector Architecture

An initial sector architecture was defined to roughly parallel the layered approach used for air traffic control. It features an N = 3 reuse factor for the top three levels, and N = 7 for the bottom level. This approach would require sub-banding of frequencies for each sector layer, as well as separate sub-bands for uplinks and

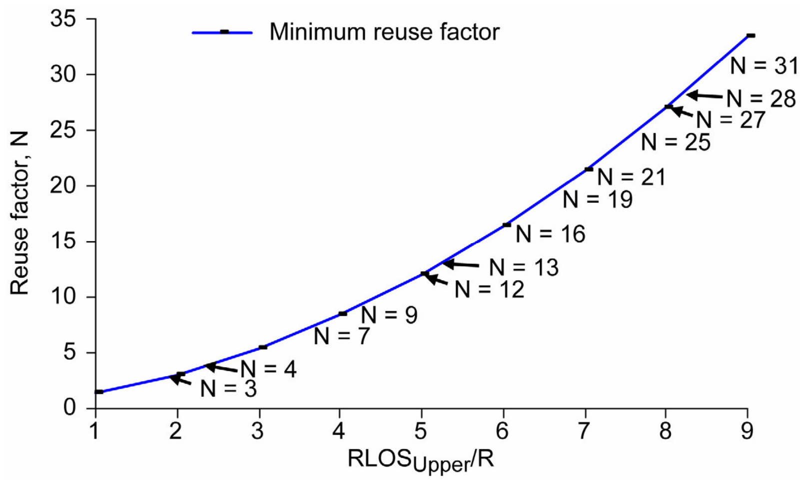


Figure 18.—Required reuse factor based as a function of $RLOS_{Upper}/R$.

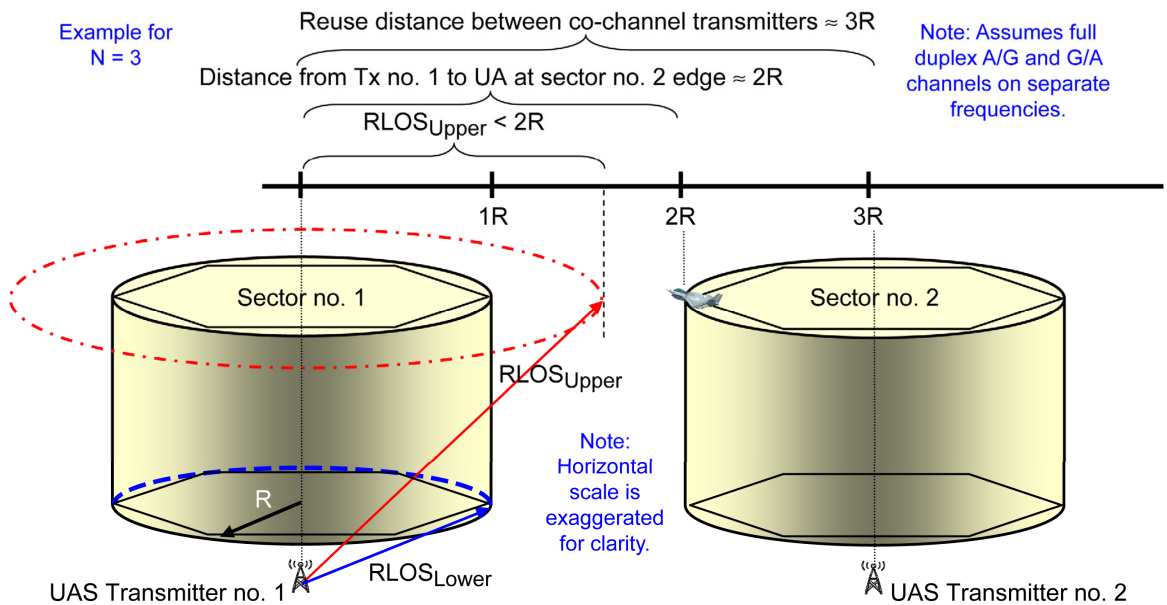
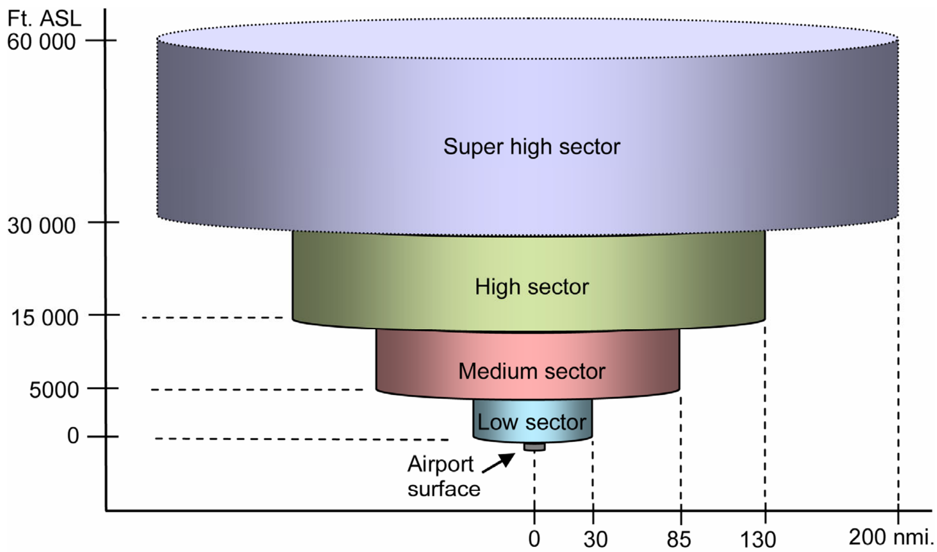


Figure 19.—Illustration of sector architecture constraints.

downlinks, to avoid co-channel interference between layers[11] and between uplinks and downlinks. Figure 20 illustrates this architecture and provides a table listing its physical parameters. Also, Figure 21 shows Medium Sector and Super High Sector coverage patterns overlaid a map of the United States. Figure 21 shows that by tiling with the hexagons, but “sectorizing” with circles means that about 21 percent of every sector is overlapped by adjacent sectors.[12] This is to avoid coverage gaps.

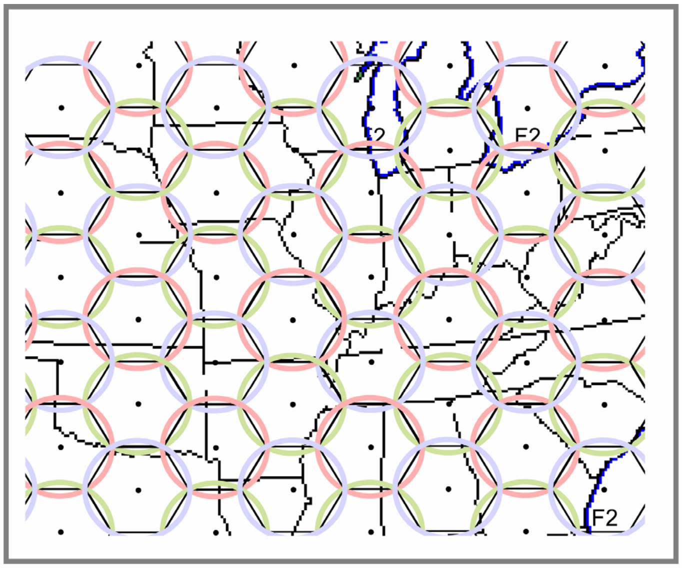


Cylindrical sectors	Super high sector	High sector	Medium sector, TMA	Low sector, airport
Sector radius, nmi	200	130	85	30
Sector top, ft	60 000	30 000	15 000	5000
Sector bottom, ft	30 000	15 000	5000	0
Sector height, nmi	4.9	2.5	1.6	0.8
Circular sector area, nmi^2	125 664	53 093	22 698	2827
Hexagonal sector area, nmi^2	103 923	43 908	18 771	2338
Hexagonal sector volume, nmi^3	513 107	108 394	30 893	1924
Ratio: circular/hexagonal area	1.21			
$RLOS_{top}$, nmi	301	213	151	87
$RLOS_{bottom}$, nmi	213	151	87	0
$RLOS_{top}/RLOS_{bottom}$	1.41	1.41	1.73	
$RLOS_{top}$/sector radius	1.51	1.64	1.77	2.90
Cluster size N	3	3	3	7
Reuse distance –1 (= Q –1)	2.00	2.00	2.00	3.58

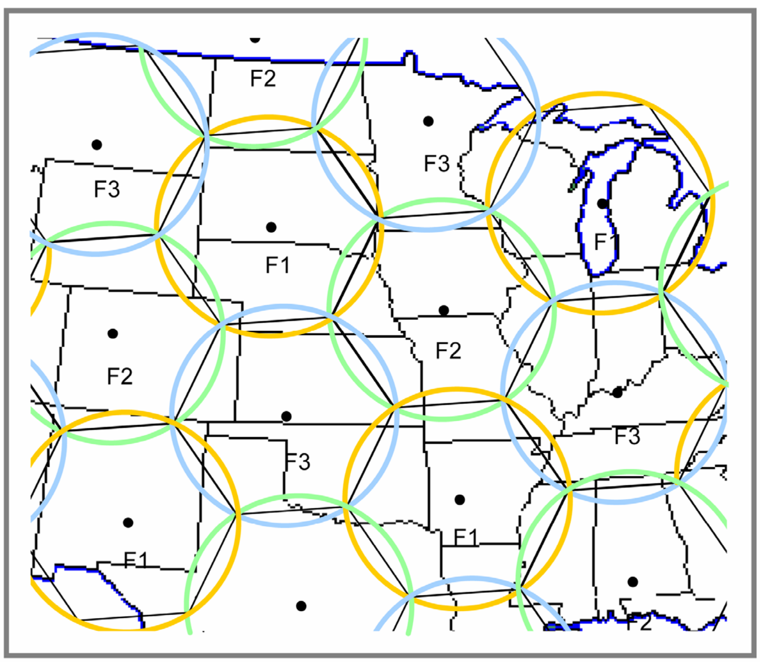
Figure 20.—Multilevel sector architecture parameters.

[11] Please note that in any particular sector layer, the RLOS between aircraft in that sector and the associated ground radio facility pass right through any lower layer sector. Without sub-banding, that is, providing a separate band of frequencies for each of the sector layers, the co-channel interference problem is significantly more complicated. This tends to favor architectures with fewer layers.

[12] Hexagonal sector volumes were used to determine UA PIACs to avoid double counting UA due to sector overlap.



Medium sector coverage over the CONUS (R = 85 nmi)



Super high sector coverage over the CONUS (R = 200 nmi)

Figure 21.—CONUS coverage examples for multilevel sector architecture; Reuse = 3.

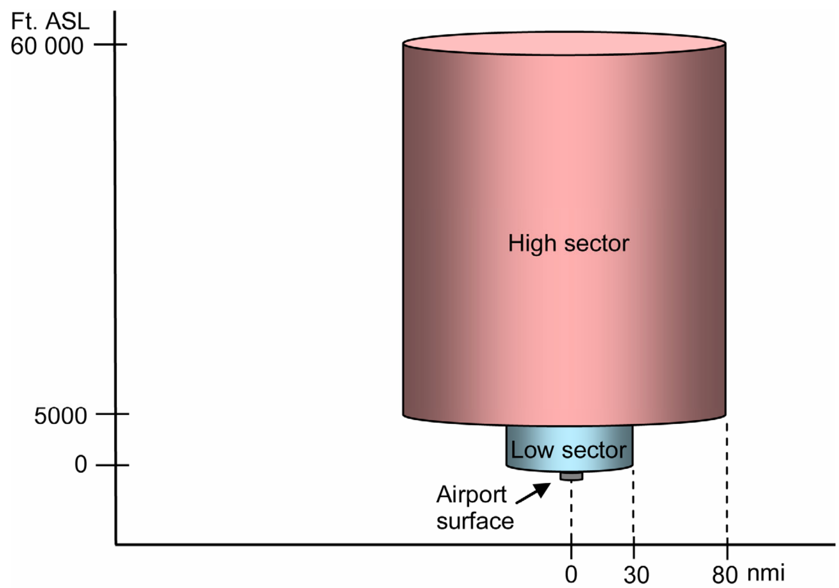
Please note that the architecture also includes an “Airport Surface” component shown in the figure for UA to UAS control facility communications on the ground. Also note that it is understood that this is an ideal sector tiling for the CONUS that does not take into consideration actual terrain effects on coverage. In a real implementation, sectors sizes and shapes would necessarily depart from the ideal uniform size cylindrical case depending on the area topography.

It is important to understand that the reuse factor determines how many frequencies are required to provide complete area coverage. For example, as shown in Figure 17 and Figure 21, for N = 3, the three

sets of frequencies representing the three sector cluster are used over and over again across the entire area of desired coverage, in our example the CONUS. In other words, if X, Y, and Z represent the number of frequency channels in each of the three respective sectors in the cluster, then X + Y + Z frequencies will cover the entire CONUS. For a sectored architecture with reuse factor "R," there would be R sets of frequencies used over and over again and "tiled" across the coverage area of interest. The right side of Figure 15 shows what this would look like for reuse factor = 7, where, as before, each color represents a different set of frequencies.

2.6.3.3 Preferred Sector Architecture

A simpler alternative two-layer sector architecture was defined to avoid multiple layers and the need for significant sub-banding (see Figure 22). It features high sector coverage from 5000 ft through 60 000 ft, an 80-mi sector radius, and a reuse factor N = 9; and a low sector with coverage from ground level through 5000 ft, a 30-mi sector radius, and a reuse factor N = 7. Just as in the earlier example, this



Cylindrical sectors	High sector	Low sector, airport
Sector radius, nmi	80	80
Sector top, ft	60 000	5000
Sector bottom, ft	5000	0
Sector height, nmi	9.1	0.8
Circular sector area, nmi^2	20 106	2827
Hexagonal sector area, nmi^2	16 628	2338
Hexagonal sector volume, nmi^3	150 511	1924
Ratio: circular/hexagonal area	1.21	0
$RLOS_{top}$, nmi	301	87
$RLOS_{bottom}$, nmi	87	0
$RLOS_{top}/RLOS_{bottom}$	3.46	0
$RLOS_{top}$/sector radius	3.77	2.90
Cluster size N	9	73
Reuse distance –1 = Q –1	4.20	3.58

Figure 22.—Preferred sector architecture parameters.

architecture also includes an “Airport Surface” component not shown in the figure for UA to UAS control facility communications on the ground. It requires separate sub-bands for uplinks and downlinks to provide co-channel interference protection.

2.6.4 Link Budget Results

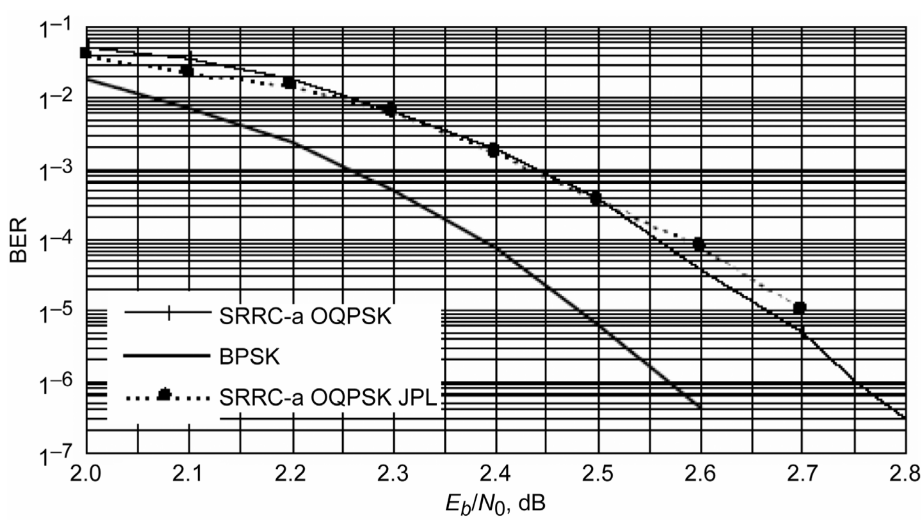
Link budgets were performed for both sector architectures to derive acceptable bandwidth and power parameters for each of the UAS control and ATC communications links. All link budgets were based on the following assumptions:

- Required BER = 10^{-6}
- At least 10 dB required link margin

The selection of a BER of 10^{-6} was based on good engineering practice for similar links and on earlier work in Access 5, which recommended this value (ref. 10). The Access 5 reference also cited ongoing development of the STANAG Interoperable C2 Data Link standard, which in the draft version described in the Access 5 document specified a fairly stringent BER requirement of 10^{-8}. Product literature from L–3 Communications for the UA communications transceivers for Global Hawk and Predator also cites product BER performance of less than 10^{-8}. Depending on the type and amount of FEC coding used, the increase in E_b/N_0 needed for 10^{-8} versus 10^{-6} BER performance would range from about 0.5 to 2 dB for additive white gaussian noise (AWGN) channel, potentially more for a fading channel. Figure 23 illustrates the bottom end of that range with a highly coded SRRC OQPSK example.

The 10-dB required link margin was specified as a reasonable value to accommodate excess path losses due to multipath and fading, and is a typical target value used in aeronautical link budgets.[13] Though this is simplification of an important performance issue, detailed discussion is beyond the scope of this study.

The two architectures provided similar performance, except that the upper two layers in the multilayered architecture, because of their sector radii, necessarily offer higher free space path loss in their link budget performance than the two relatively small radius sector sizes in the two-layer architecture. Even then, all links are able to meet or exceed the 10-dB margin.



[13] Fading depth due to simple two-ray path loss calculations is highly dependent on ground antenna height, multipath incidence angles, and receive antenna beam pattern, but fade margins of 2 to 6 dB would not be unreasonable at the notional L-band frequencies assumed for this study.

Figure 23.—Measured BER versus E_b/N_0 for SRRC-a OQPSK system with CC FEC coding (ref. 12).

An example of the two-layer architecture link performance for the UAS control A/G downlink is provided in Table XIX. Aside from ensuring that the link performance provided adequate link margin, the principal outputs of this step were the channel bandwidths needed to calculate the total UAS control and ATC communications bandwidth. In the example shown in the figure, the channel bandwidth was calculated to be 60 800 Hz.

Table XVII.—Example link budget results[a]

Link budget parameter	High sector 5000 to 60 000 ft	Low sector 0 to 5000 ft	Airport surface
Air-to-ground slant range, nmi	80	30	5
Transmit power, dBm	41.8	41.8	41.8
Transmit line losses, dB	–3	–3	–3
Transmit antenna gain, dBi	0	0	0
Transmit EIRP, dBm	38.8	38.8	38.8
Free space path loss, dB	136.6	128.1	112.5
Receive antenna gain, dBi	6	6	6
Receive line losses, dB	–2	–2	–2
Received power, dBm	–93.8	–85.3	–69.8
Receiver noise figure, dB	8	8	8
External noise figure, dB	1.3	1.3	1.3
System noise figure, dB	10.1	10.1	10.1
Noise floor, kT_0B, dBm	–126.2	–126.2	–126.2
Receiver noise power, dBm	–116.0	–116.0	–116.0
Theoretical E_b/N_0 dB	3.0	3.0	3.0
Theoretical C/N, dB	3.6	3.6	3.6
Implementation losses, dB	2	2	2
Required C/N, dB	5.6	5.6	5.6
Received C/N, dB	22.2	30.7	46.3
Margin, dB	16.6	25.1	40.7

[a]SRRC (α = 0.5) OQPSK with concatenated RS (255, 233) and rate ½, k = 7 convolutional FEC coding.

2.6.5 Calculating Total UAS C&C Communications Bandwidth

For this step it was necessary to select appropriate UA densities to determine the UA PIAC for the high sector and low sector service volumes in the sector architecture. For this, COCR and EUROCONTROL FCS test service volumes similar in size to the notional architecture sector volumes were used (see Table XVIII). The selected service volumes are bold in the table.[14] Please note that for the airport surface case a PIAC without a density is listed because a volume estimate is not appropriate for the surface coverage. Thus, the UA PICA for the airport surface case is calculated directly as a percentage of the total PIAC. The UA densities/PIACs corresponding to the selected COCR/EUROCONTROL service volumes were applied to the sector architecture assumptions along with the individual channel bandwidths calculated from the link analysis, and the results were tabulated. Table XIX shows the resulting estimated total bandwidth (about 17.1 MHz) for the UAS control communications links, assuming Configuration B (networked links) and based on the concatenated RS (255, 233) and ½ rate convolution FEC coding case. Calculated total bandwidths for the other link cases are provided graphically in the next section.

[14]As shown in the figure, the aircraft density value for the Lower Sector was based on the density value for the NAS TMA high density (HD) Phase 1, because of the similarity in sector volume. The argument might be made that a Phase 1 density might not be appropriate because of the time frame involved; however, the COCR NAS TMA HD Phase 2 density is the same as the Phase 1 density, which is the same as the EUROCONTROL TV2.1 TMA small service volume density.

Table XVIII.—FCS test service volumes used to provide suitable total UA PIAC densities

Service volume	Total PIAC	Volume, nmi^2	Total aircraft, nmi^2	UA density: aircraft, nmi^2	
				5%	10%
COCR—NAS Airport HD Phase 1	200	--------	--------	---------	--------
COCR—NAS Airport LD Phase 1	12	--------	--------	---------	--------
COCR—NAS Airport HD Phase 2	290	--------	--------	---------	--------
COCR—NAS Airport LD Phase 2	19	--------	--------	---------	--------
COCR—NAS TMA LD Phase 1	14	3039	0.0046	0.0002	0.0005
COCR—NAS TMA HD Phase 1	16	2831	0.0057	**0.0003**	0.0006
COCR—NAS En Route LD Phase 1	24	20,782	0.0012	0.0001	0.0001
COCR—NAS En Route HD Phase 1	24	5119	0.0047	0.0002	0.0005
COCR—NAS TMA LD Phase 2	39	9240	0.0042	0.0002	0.0004
COCR—NAS TMA HD Phase 2	44	7691	0.0057	0.0003	0.0006
COCR—NAS En Route LD Phase 2	59	33,388	0.0018	0.0001	0.0002
COCR—NAS En Route HD Phase 2	45	10,132	0.0044	0.0002	0.0004
COCR—NAS En Route Super Sector	95	31,996	0.0030	0.0001	0.0003
EUROCONTROL—TV1 Airport Total	200	--------	--------	---------	--------
EUROCONTROL—TV1a Airport Surface	**264**	--------	--------	---------	--------
EUROCONTROL—TV1 Airport in Flight	28	259	0.1004	0.0050	0.0100
EUROCONTROL—TV2.1 TMA Small	44	7691	0.0057	0.0003	0.0006
EUROCONTROL—TV2.2 TMA Large	53	18,056	0.0029	0.0001	0.0003
EUROCONTROL—TV3.1 ENR Small	28	10,132	0.0028	0.0001	0.0003
EUROCONTROL—TV3.2 ENR Medium	62	33,379	0.0019	0.0001	0.0002
EUROCONTROL—TV3.3 ENR Large	204	134,957	**0.0015**	0.0001	0.0002
EUROCONTROL—TV3.4 ENR Super Large	522	539,829	0.0010	0.00005	0.0001

Table XIX.—Calculated total UAS control communications bandwidth result

Sector architecture parameters	High sector	Low sector	Airport surface	Total
Sector radius, nmi	80	30	----------	----------
Sector top, ft	60,000	5000	----------	----------
Sector bottom, ft	5000	0	----------	----------
Sector height, nmi	9.1	0.8	----------	----------
Circular sector area, nmi^2	20,106	2827	----------	----------
Hexagonal sector area, nmi^2	16,628	2338	----------	----------
Hexagonal sector volume, nmi^3	150,511	1924	----------	----------
Cylindrical sector volume, nmi^3	181,998	2327	----------	----------
Ratio, circular/hexagonal area	1.21	----------	----------	----------
RLOS at top, nmi	301	87	----------	----------
RLOS at bottom, nmi	87	0	----------	----------
$RLOS_{top}/RLOS_{bottom}$	3.46	----------	----------	----------
$RLOS_{top}$/sector radius	3.77	2.90	----------	----------
Reuse factor	9	7	1	----------
Reuse distance – 1 (Q – 1)	4.20	3.58	----------	----------
Total aircraft density (no. per nmi^3)	0.00151	0.00565	----------	----------
Percentage of UA in the NAS	10	10	10	----------
UAS aircraft density (no. per nmi^3)	0.000151	0.000565	----------	----------
Computed peak UA count per sector	23	1	26	----------
Control link—number of downlink/uplink channels	207	7	26	240
Control link—downlink channel bandwidth, Hz	60,800	60,800	60,800	60,800
Control link—uplink channel bandwidth, Hz	10,600	10,600	10,600	10,600
Control link—total downlink bandwidth, Hz	12,585,600	425,600	1,580,800	14,592,000
Control link—total uplink bandwidth, Hz	2,194,200	74,200	275,600	2,544,000
Control link—total uplink + downlink BW, Hz	14,779,800	499,800	1,856,400	17,136,000

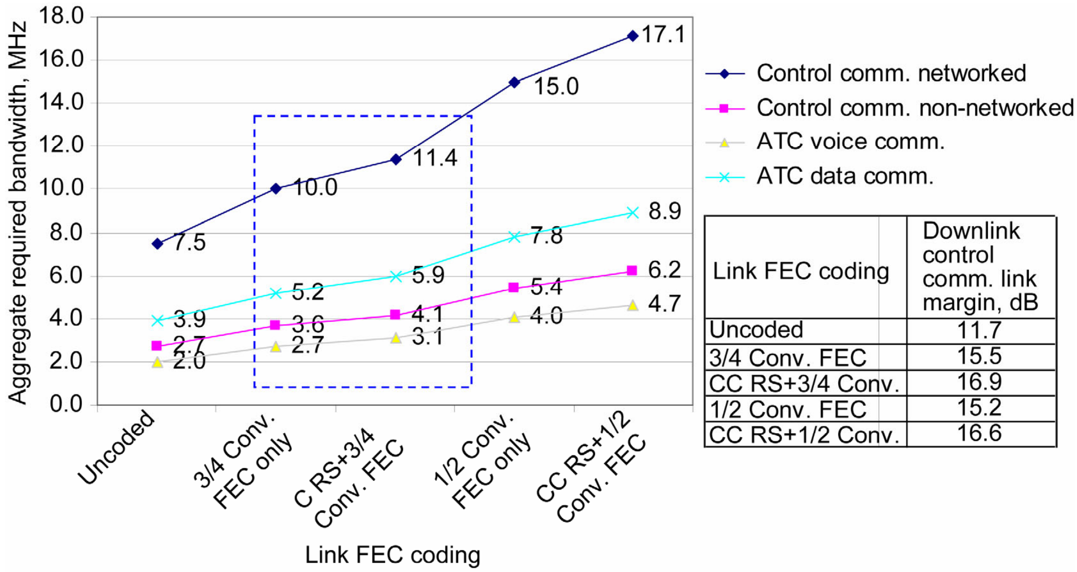
2.6.5.1 Required Bandwidth Estimation Sensitivity

It is probably not surprising to note that the total required UAS communications bandwidth requirements were quite sensitive to certain parameters and study assumptions, including the following:

- UA peak counts
  - UA were assumed to be 10 percent of the total PIAC; a different value based on emerging plans and future operational practice linearly scales the results.
- UAS control communications link architecture configuration assumptions
  - Required UAS control communications data capacity was estimated for two configurations defined by STANAG 4586 (ref. 1), corresponding to two alternative UAS ground control station to UA link architectures. One configuration (Configuration A) assumed a non-networked, native or proprietary type RF link with some security overhead, while the second configuration (Configuration B) implied an RF link that included overhead for standards-based security, STANAG 4586 DLI wrappers, and transport and/or network layer protocols.
    - Configuration B resulted in significant network and transport layer protocol overhead on the A/G links.
    - The Configuration A non-networked assumption significantly reduced required bandwidth.
- Data rate requirements of the UAS Command and Status/Telemetry messages
  - These are highly dependent on update rates associated with varying degrees of autonomy. Conservative values were assumed to upper bound the aggregate rate, based on low to moderate autonomy UAS.
  - In addition, for the networked Configuration B, a conservative assumption was made that multiple command/status messages were not combined into IP datagram payloads, that is, each IP data payload consisted of only one command/status message.
- The channel modulation selected and amount of link FEC coding necessary to increase link margin to accommodate excess path losses, directly impacted required channel bandwidth.
  - A range of link FEC coding alternatives were used to provide a range of total required bandwidth.
- Sector architecture, including sector size and “layering,” and the corresponding selection of reuse parameters to mitigate co-channel interference.

2.6.5.2 Required Bandwidth Results

Figure 24 graphically illustrates required total UAS C&C bandwidth estimates for the two-layered architecture for each link type and their sensitivity to overhead and link FEC coding assumptions. A box has been placed around the values that provide a reasonable range of bandwidth requirements, while still providing suitable performance. It should be noted that the multilayer architecture provided slightly worse performance and resulted in slightly higher bandwidth estimates.



Link FEC coding	Downlink control comm. link margin, dB
Uncoded	11.7
3/4 Conv. FEC	15.5
CC RS+3/4 Conv.	16.9
1/2 Conv. FEC	15.2
CC RS+1/2 Conv.	16.6

Figure 24.—Required total UAS communications bandwidth estimates and their sensitivity to overhead and link FEC coding assumptions.

3.0 Conclusions and Recommendations

Given the fact that UAS civil and private aviation in the NAS is still in its earliest stages, the range of possibilities for implementing a broad-based means of providing both UAS control communications and ATC communications is fairly wide open. Because of its focus on the need to identify potential future UAS frequency spectrum needs in support of WRC activities, this study concentrated on just one of several possible means of providing these capabilities, that is, by way of UA relay. As mentioned earlier, other potential architectures are being considered by RTCA SC–203, if not by other organizations. Even within this one architectural approach there is still a lot of leeway in developing the assumptions and the notional architecture design decisions needed to make the UAS communications bandwidth estimates. The sensitivity of this estimation process to these design decision assumptions and selection of certain key parameters was discussed in the preceding section and this demonstrated the inadvisability of trying to derive a single number to estimate total bandwidth requirements. Therefore for this study a range of estimated bandwidth requirements was developed to provide bounds, based on the stated configurations and assumptions.

For the selected notional architecture, the findings based on modest FEC coding, such as provided by the two rate ¾ cases provide the most reasonable compromise between performance and bandwidth within the range of results. In particular, the concatenated (CC) Reed Solomon (255, 223) block encoding and ¾ rate convolutional FEC coding case provided significant excess path margin for protection against interference and signal degradations, including protection against burst errors. These two cases resulted in the following bandwidth estimates:

- Control communications bandwidth estimates on the order of 10 to 11.4 MHz for the networked configuration
  - 8.5 to 9.7 MHz for the UA to UAS radio control station downlink
  - 1.5 to 1.7 MHz for the UAS radio control station to UA uplink
- Control communications bandwidth estimates on the order of 3.6 to 4.1 MHz for the non-networked configuration
  - 3.3 to 3.8 MHz for the UA to UAS radio control station downlink
  - About 0.3 MHz for the UAS radio control station to UA uplink
- ATC voice communications bandwidth estimates on the order of 2.7 to 3.1 MHz, split equally between the uplink and downlink
- ATC data communications bandwidth estimates on the order of 5.2 to 5.9 MHz
  - About 3.3 to 3.8 MHz for the downlink
  - About 1.9 to 2.1 MHz for the uplink

The notional architecture used to estimate total bandwidth requirements allowed for significant link margin because of the modest sector radii. Other possible architectures may be more efficient (though the initial architecture resulted in poorer performance in almost every respect).

In closing, some additional concluding remarks and recommendations can be made. Because a detailed design was beyond the scope of this task, several relevant issues were not considered. These included the following:

- Co-site interference issues, both on the UA and for the UAS ground radio facilities, not considered for this study, need to be explored. Assuming that both the control communications and ATC communications use the aeronautical L-band, for example, (and assuming sufficient available bandwidth could be identified) allowed for straightforward analysis; however,

simultaneous transmission on these links present serious design challenges, especially on the UA, to mitigate potential co-site interference.

- The potential impacts of sub-banding need to be addressed. Though in certain respects it might be easier to identify noncontiguous “chunks” or sub-bands of spectrum for the different control and ATC communications links than it would be to find 10 to 20 contiguous MHz of available bandwidth to manage, this spectrum management issue should be investigated.
- The entire issue of whether or not a national UAS communications service could be implemented was beyond the scope of this study, and to a certain extent, it does not affect the analysis. However, this study was based on a uniform design, regardless of how and by whom it would be implemented and/or operated, and the study results are therefore dependent on this assumption.
- Just as with the COCR, for estimation purposes, this study nominally assumed a uniform density of aircraft throughout a sector/service volume. In reality, this often is not the case, as both manned and unmanned aircraft would be concentrated along particular corridors or “hot spots.” This could affect UAS bandwidth requirements and should be considered as a future topic of study.
- As stated earlier, for the purposes of link efficiency and interference mitigation it might be advisable to combine the ATC voice and data links. Furthermore, each of the uplink/downlink pairs might be implemented via simplex or full duplex links, potentially reducing the number of UAS radio facility to UA links to as few as two. In the limit, control communications and ATC communications message traffic could be combined and implemented via a single link, though this potential single point of failure configuration might present too much risk. This issue needs further investigation.
- Though the target 10-dB link margin was mostly exceeded over the range of link parameter values assumed for the link analyses; further work in the area of required link margin, including acceptable excess path loss, should be pursued.

Appendix A—List of Acronyms and Abbreviations

The following list identifies acronyms and abbreviations used throughout this report.

A/G	air/ground
AOA	autonomous operations area
ATC	air traffic control
ATS	air traffic services
AWGN	additive white gaussian noise
AV	air vehicle
BER	bit error rate
BLOS	beyond line of sight
BT	bandwidth x symbol duration
C4I	command, control, communications, computers, and intelligence
C&C	Control and ATC Communications
CC	concatenated
CCI	command and control interface
CCISM	command and control interface specific module
CCSDS	Consultative Committee for Space Data Systems
CDMA	code division multiple access
COCR	communication operating concept and requirements
CoS	class of service
CPM	continuous phase modulation
CUCS	Core UAV Control System
D	distance
DSB–AM	double sideband amplitude modulation
DL	downlink
DLI	data link interface
E_b/N_0	energy per bit over noise power spectral density
FAA	Federal Aviation Administration
FCS	future communications study
FDMA	frequency division multiple access
FEC	forward error correction
FM	frequency modulation
FQPSK	Feher patented QPSK
GMSK	gaussian minimum shift keying
HCI	human computer interface
HD	high density
Hz	Hertz
ICAO	International Civil Aviation Organization
ICV	integrity check value
ID	identification
IFR	instrument flight rules
IP	internet protocol
L&R	launch and recovery
ITU	International Telecommunications Union
LD	low density
LOS	line of sight
MHz	Megahertz
n	Path loss exponent
NAS	National Airspace System

NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
OQPSK	offset quadrature phase shift keying
P25	Project 25
PIC	pilot in charge
PIAC	peak instantaneous aircraft count
PIC	pilot in charge
QoS	quality of service
QPSK	quadrature phase shift keying
R	radius
RF	radiofrequency
RLOS	radio line of sight
SCPS	Space Communications Protocol Standard
S/I	signal to interference ratio
SOQPSK	shaped offset quadrature phase shift keying
SRRC	square root raised cosine
SSPA	solid state power amplifier
TCM	trellis coded modulation
TCP	transmission control protocol
TCP/IP	transmission control protocol/internet protocol
TDMA	time division multiple access
TMA	terminal maneuvering area
UA	unmanned aircraft
UAS	unmanned aircraft system
UAT	universal access transceiver
UAV	unmanned aerial vehicle
UCS	UAV control system
UDP	user datagram protocol
UL	uplink
VDL	very high frequency digital link
VHF	very high frequency
VSM	vehicle specific module
WRC	World Radiocommunications Conference

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
There are significant activities taking place to establish the procedures and requirements for safe and routine operation of unmanned aircraft systems (UAS) in the National Airspace System (NAS). Among the barriers to overcome in achieving this goal is the lack of sufficient frequency spectrum necessary for the UAS control and air traffic control (ATC) communications links. This shortcoming is compounded by the fact that the UAS control communications links will likely be required to operate in protected frequency spectrum, just as ATC communications links are, because they relate to “safety and regularity of flight.” To support future International Telecommunications Union (ITU) World Radio Conference (WRC) agenda items concerning new frequency allocations for UAS communications links, and to augment the Future Communications Study (FCS) Technology Evaluation Group efforts, NASA Glenn Research Center has sponsored a task to estimate the UAS control and ATC communications bandwidth requirements for safe, reliable, and routine operation of UAS in the NAS. This report describes the process and results of that task. The study focused on long-term bandwidth requirements for UAS approximately through 2030.

15. SUBJECT TERMS
Pilotless aircraft; Command and control; Aircraft communication; Bandwidth; Spectrum

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